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*Technical Report*

**TRANSMISSION BY THE EARTH'S ATMOSPHERE OF THERMAL ENERGY  
FROM NUCLEAR DETONATIONS ABOVE 50-KM ALTITUDE**

*Prepared for:*

OFFICE OF CIVIL DEFENSE  
DEPARTMENT OF DEFENSE  
WASHINGTON 25, D.C.

CONTRACT NO. OCD-OS-62-135, TASK III

STANFORD RESEARCH INSTITUTE

MENLO PARK, CALIFORNIA

**\*SRI**

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April 30, 1963

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SRI Project No. IMU-4021-302

Approved:

This report has been reviewed in the Office of Civil Defense and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Office of Civil Defense.

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# ABSTRACT

The extensive literature on transmission of solar energy by the earth's atmosphere supports transmission estimates for the average clear day at sea level ranging from around 80% for vertical rays to around 15% for rays 5° above horizontal. Cloud transmission (on the basis of 100% for a clear day) varies from around 30% for light cloud to around 3% for a dense cloud. Transmission factors can be computed when the more important atmospheric parameters are known, namely, (1) thickness, liquid content, and droplet size of clouds; (2) size and volume concentration of solid haze particles; (3) reflectivity of the earth's surface.

Theoretically estimated upper limits to the unattenuated energy flux from a 1000-mt detonation (taken from a companion study to the present one), combined with the above estimates of atmospheric transmission give ignition radii ranging from 250 km at 50-km burst height to 0 km at 240-km burst height for the average clear day at sea level.

A conscious attempt has been made in this study to give upper limits to both transmission factors and energy fluxes. Thus, in real world situations, the ground effects are expected to be substantially less extensive and less intensive than these estimates would indicate.

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## I INTRODUCTION

The possibility of large nuclear detonations at high altitudes setting fire to vast areas of the earth has been raised by numerous persons. In a previous report<sup>1\*</sup> an attempt was made to derive theoretically the radii of ignition circles as a function of detonation yield and burst altitude, neglecting attenuation in the lower atmosphere. In this report we consider the effects of atmospheric attenuation on ignition circle radii.

In general, our knowledge of the thermal emissions from nuclear detonations both within and outside the atmosphere are sufficiently detailed that one could predict within reasonable limits the energy flux on any surface were it not for the attenuating properties of the earth's atmosphere. If one knew which one of an almost infinite variety of atmospheric conditions existed at a given time, then the calculation of the transmission for nuclear detonation radiation might be tedious but it would be reasonably accurate.

However, the earth's atmosphere is not constant; it changes as frequently as does the weather. Therefore, a certain degree of variability and unpredictability will persist through all our estimations of its transmissivity. In spite of these problems of unpredictability, this report contains estimates derived from existing knowledge of the transmission of the earth's atmosphere for the radiation from nuclear detonations. Present knowledge is based upon that information which is commonly collected by meteorological services.

In approaching this problem, one recognizes three broad categories of conditions common to the earth's atmosphere: (1) an average clear day, (2) a hazy or smoggy day, and (3) a cloudy, overcast, or foggy day. Another important variable to consider is the altitude above the earth of the nuclear detonation. This report considers primarily the altitude range above 50 km. The major reason for emphasizing this altitude range

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\* Numbered references are listed at the end of this report.



is that detonations at these altitudes give thermal radiation damage to the earth over far larger areas than those at or near the surface. Also, the attenuation geometry is particularly simple since clouds and haze all lie in layers within 10 km of the surface -- well removed from the burst region.

The chief expected characteristics of the thermal emission from nuclear detonations above 50 km have been previously described.<sup>1</sup> Briefly, the fireballs are spherical to 80-km burst altitude, giving a thermal pulse lasting less than 1 sec (insensitive to yield). As the burst altitude is increased above 80 km, the effective reradiating fireball is still at the 80-km level, expanding to the form of a pancake whose radius is around  $h-80$  km (where  $h$  is the detonation height) and whose thickness is around 10 km. If a mean radiating temperature can be defined, it lies well above the 6000°K to 7000°K characteristic of detonations near the earth's surface. Therefore, the thermal energy emitted exhibits a spectrum of photon wavelengths shifted toward the ultraviolet relative to that from the near-surface burst. This alteration in the energy spectrum reduces to lesser significance the attenuation by water vapor in the atmosphere, since much of that attenuation occurs in the infrared region.

This report contains a summary of the best available atmospheric transmission data for the average clear day, for varying degrees of haziness, and for the cloudy day. The vast majority of available data comes from measurements of radiation from the sun at the earth's surface.

In addition, we attempt to show the direction in which additional effort should be applied in improving our ability to estimate atmospheric transmission.

Finally, the summarized data on atmospheric transmission is applied in computing upper limits to the ignition radii for 100-, 1000-, and 10,000-mt nuclear detonations for altitudes above 50 km.

## II GENERAL CONSIDERATIONS

The transmission of thermal energy from a nuclear detonation to a point on the ground surface of the earth occurs by two major routes: (1) direct radiation which passes without deviation from the detonation point to the receiving point, (2) radiation initially starting in another direction but which is scattered by haze, clouds, reflecting earth surfaces, or air molecules (Rayleigh scattering) back toward the receiver. For example, for a cloud-covered earth, almost 100% of the energy arriving at the ground from the sun is diffuse; that is, every photon which arrives at the ground has made many changes in direction from its original path as it left the source. Most of the complexity and a great part of the uncertainty in determining or estimating atmospheric transmission lies in the estimation of this diffuse component.

The diffuse component of radiation arriving from the sun is somewhat greater than the diffuse component from a nuclear detonation. Hence, the transmission of the earth's atmosphere will be greater for solar radiation than for radiation from a nuclear detonation. (The sun irradiates the earth's atmosphere above a given point on the earth uniformly, whereas a nuclear detonation above 50-km altitude irradiates the earth's atmosphere somewhat non-uniformly because of the decrease of the radiant intensity by the inverse square law. The source volume which gives the skylight or diffuse component is thus much larger for sunlight than for thermal radiation from nuclear bursts.) The transmission values obtained from extensive studies of solar radiation will therefore be upper limits to the atmospheric transmission factors appropriate for radiation from high altitude nuclear bursts.

In spite of the difference between the diffuse transmission of sunlight and the radiation from nuclear detonations, in certain instances such as the average clear day at sea level the diffuse component is a small fraction of the total transmitted energy, so that differences in this small fraction can be ignored.

The data on sunlight has been gathered to satisfy several objectives among which are: (1) determination of the solar constant; (2) measurement

of parameters important to determining the heating of the atmosphere by the sun; and (3) determination of the proper exposure in photography under various atmospheric conditions. From the standpoint of the present problem, the most complete and directly connected single study is one performed to determine the proper photographic exposure for varying conditions of sunlight and skylight.<sup>2</sup> The energy region studied<sup>2</sup> was between 4200A and 7000A (the approximate limits of the standard luminosity curve for the human eye).

It is interesting to establish the extreme upper limits of the ignition circles centered at ground zero of a nuclear detonation. The theoretical maximum surface area that can be exposed from a radiation source at a given altitude is limited by the curvature of the earth. Measuring distance along the earth's surface from ground zero, the maximum radius of the exposed areas is the extreme limit of the ground range (shown as a function of altitude in Fig. 1). The extreme limit of the ground range, EGR, is defined by the equation

$$\text{EGR} = R \cos^{-1}(R/(R+h))\text{km} \quad (R=6370 \text{ km}) \quad (1)$$

where

EGR is measured along the earth's surface from ground zero in kilometers),

R is the earth's radius, and

h is the altitude above the earth's surface.

A ground point at the extreme limit of the ground range is one at which the local apparent elevation angle of the radiation source is zero degrees above the horizontal. Figure 2 gives a cross section illustrating ground range and source elevation angle.

Of the total ground area exposed to radiation from a nuclear detonation, that part which receives energy along paths closest to horizontal is the largest fraction of the total. These nearly horizontal paths also exhibit the greatest atmospheric attenuation because their lengths in the attenuating medium are greatest. Somewhat greater effort was devoted to the search for measurements of solar energy transmission at

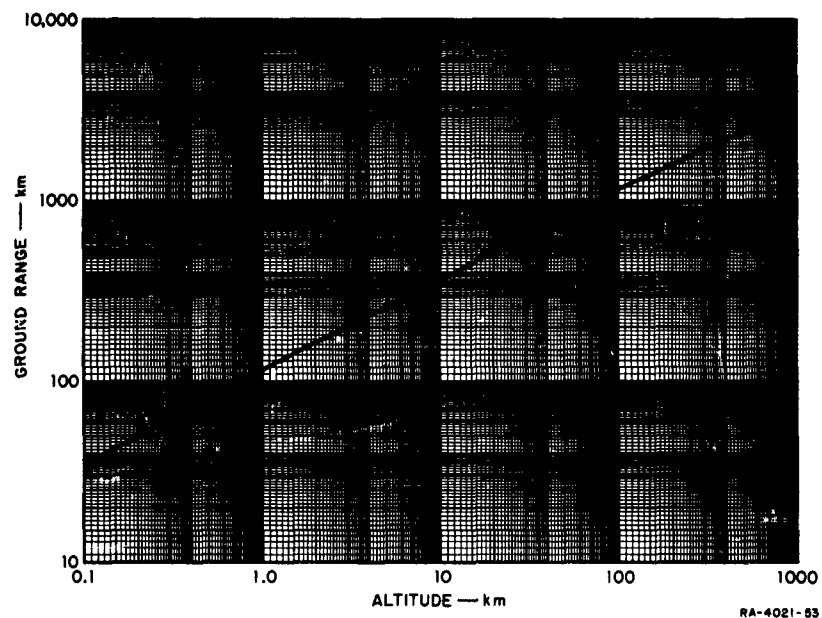


FIG. 1 THE THEORETICAL LIMIT TO THE LENGTH OF THE GROUND RANGE (measured along the earth's surface from ground zero) AS A FUNCTION OF ALTITUDE ABOVE SEA LEVEL

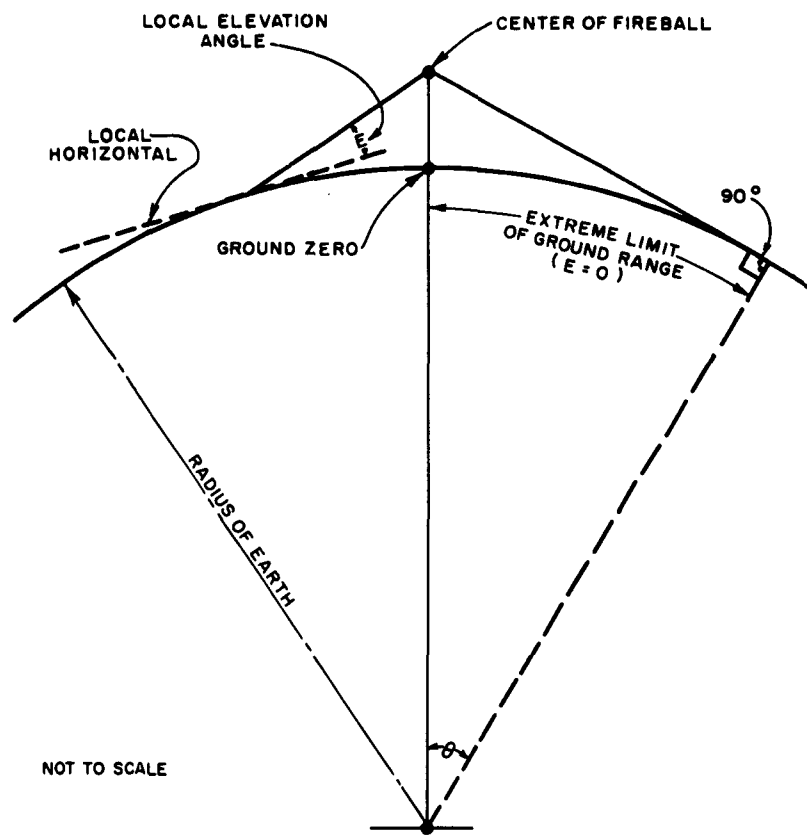


FIG. 2 CROSS SECTION OF THE EARTH ILLUSTRATING THE DEFINITIONS OF EXTREME LIMIT OF GROUND RANGE AND LOCAL ELEVATION ANGLE

low elevation angles above the horizon, because small uncertainties in this region give large uncertainties in determining the effectively exposed area.

It should not be inferred that because an area is exposed it is necessarily ignited. As is shown later in the report, only in extremely unlikely circumstances will energy fluxes be sufficient for ignition near the extreme ground range. However, this geometrical configuration will be described below as if ignition could occur at significant fractions of the extreme ground range.

To illustrate the terminology adopted for describing the effects of low source elevation angles, consider Fig. 2. Assume a detonation of some fixed yield results in a fireball at some altitude above ground zero. Let us observe the fireball from a mobile station that moves along the earth's surface from ground zero to the extreme limit of the ground range. As seen from the mobile ground station, the elevation angle of the source is  $0^\circ$  at the extreme limit of the ground range and  $90^\circ$  at ground zero. Assume that the mobile ground station is covered with a hemisphere of cloth that ignites at some very low threshold energy flux. Such a hemisphere always has a region which is optimally oriented (that is, it receives the greatest possible energy flux from the fireball). With no attenuating atmosphere, the energy flux on the optimally oriented surface would follow the inverse square law as the mobile station proceeded from ground zero to the EGR. If the yield were barely sufficient in the absence of the atmosphere to ignite the optimally oriented surface at EGR, atmospheric attenuation would reduce the ignition radius from the theoretical maximum. The new ignition radius would be at some point where the elevation angle of the source was  $E$ . The angle  $E$  can be considered the minimum elevation angle at which the optimally oriented surface can be ignited.

Assuming such a minimum allowable elevation angle has been determined for ignition of a given material by a given nuclear detonation, the ignition radius (relative to the extreme ground range) is shown in Fig. 3. Considering the curve for the 80-km burst height, it is apparent that a  $10^\circ$  minimum elevation angle decreases the radius of the ignited area

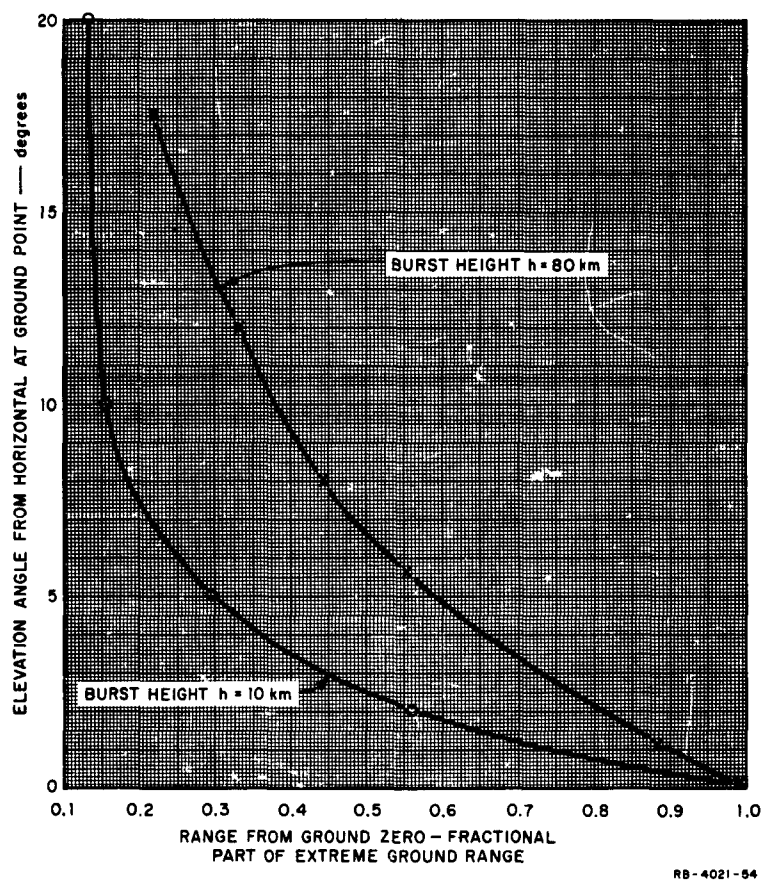


FIG. 3 THE EFFECT OF ATTENUATION-DETERMINED MINIMUM ELEVATION ANGLES ON THE EFFECTIVE GROUND RANGE FOR TWO DIFFERENT BURST HEIGHTS

to 38% of that for the maximum exposed area. Thus the ignited area has been reduced by atmospheric attenuation to  $(0.38)^2$  or 14.5% of the maximum exposed area.

Equation 2 was used in the computations required for the construction of Fig. 3, and should be used to extend Fig. 3 to other detonation altitudes, if interpolation is felt to be too inaccurate for a given purpose.

$$\tan E = \frac{-(R/(R+h)) + \cos \theta}{\sin \theta} \quad (2)$$

where E is the elevation angle of the detonation point as seen from some ground point, R is the radius of the earth, h is the altitude of the fireball, and  $\theta$  is the angle subtended at the earth's center by the arc from ground zero to the ground point being considered.

Having established that small changes in minimum elevation angle can give large changes of effects circle radii, we now consider a convenient terminology for describing how atmospheric transmission varies with source elevation angle.

As the direct radiant energy path from a source (the sun or a nuclear detonation) becomes more nearly horizontal (as measured locally at the ground point), the path length through the attenuating atmosphere increases. A common term used to express this effective attenuation path is the "optical air mass". An optical air mass of 1.0 is the total atmospheric mass per unit area encountered by a ray passing vertically through the atmosphere (considering only the permanent gases of the earth's atmosphere). One optical air mass is equivalent to an 8-km path at sea level. Table I shows the number of optical air masses as a function of the apparent elevation angle of the radiation source (Table I includes effect of curvature of the earth). The attenuation of the direct component from the source is exponentially dependent upon the optical air mass. When the diffuse component is included the functional dependence of attenuation with air mass is more complex.



Table I  
OPTICAL AIR MASS FOR VARIOUS APPARENT SOLAR ELEVATION ANGLES\*

Solar Elevation Above Horizon										
(°)	0	1	2	3	4	5	6	7	8	9
0		26.96	19.79	15.36	12.44	10.39	8.90	7.77	6.88	6.18
10	5.60	5.12	4.72	4.37	4.07	3.82	3.59	3.39	3.21	3.05
20	2.90	2.77	2.65	2.55	2.45	2.36	2.27	2.19	2.12	2.06
30	2.00	1.94	1.88	1.83	1.78	1.74	1.70	1.66	1.62	1.59
40	1.55	1.52	1.49	1.46	1.44	1.41	1.39	1.37	1.34	1.32
50	1.30	1.28	1.27	1.25	1.23	1.22	1.20	1.19	1.18	1.17
60	1.15	1.14	1.13	1.12	1.11	1.10	1.09	1.09	1.08	1.07
70	1.06					1.04				
80	1.02									
90	1.00									

\* For example, the optical air mass for 13 degrees is found in the row labeled 10, and the column labeled 3.

A rapid change in the magnitude of the optical air mass as the elevation angle approaches zero is apparent in Table I. Thus a decrease in elevation angle from 5° to 3° to 1° increases the number of optical air masses from 10 to 15 to 27. This rapid change in transmission with change in local elevation angle means that a circle of influence may be sharply defined in terms of elevation angle.

For those thermal effects which require such low energy fluxes that their radii of influence are potentially greater than the extreme ground range, Figs. 1 and 3 can be used in determining those radii. All that is needed in addition to Figs. 1 and 3 is the attenuation of the radiation as a function of the number of optical air masses under the various common atmospheric conditions.

### III SUMMARY OF AVAILABLE DATA ON ATMOSPHERIC TRANSMISSION

#### A. Cloudless Skies

Because of the enormous volume of solar transmission data, detailed information from a few very extensive summaries of these data will be given. Among the best summaries for this application is a survey of the luminous energy (energy to which the human eye is sensitive -- namely, between 4200A and 7000A with a peak at 5560A) arriving at variously oriented surfaces on the earth from the sun.<sup>2</sup> These measurements were made using photographic film which has a different spectral sensitivity than the human eye, coupled with special filters to expose the film only to luminous energy. For our purposes it would have been better if an unfiltered camera had been used.

Figure 4 is a curve based on computed values (from Ref. 2, Table VII) of the luminous energy arriving at a surface normal to the sun's rays (that is, optimally oriented for ignition) on the average sea level clear day. The curves shown are based primarily on experimental data compiled by Moon<sup>3</sup> for the direct component and on the experimental data of Kimball and Hand<sup>4</sup> for the diffuse component. Before the decision was made by Jones and Condit<sup>2</sup> to use the work of Moon, detailed comparisons were made with data by Kunerth and Miller,<sup>5</sup> Elvegard and Sjosted,<sup>6</sup> I. F. Hand,<sup>7</sup> and H. H. Kimball and I. F. Hand.<sup>4</sup> Minor discrepancies were found among these data, but when averaged, the data showed remarkable agreement with the curves of Moon.<sup>3</sup> Hence, the transmission factors of Fig. 4 are appropriate to the "average" clear day at sea level. Considering the variability of the experimental data about this average, transmission factors based upon it should be reliable to approximately  $\pm 30\%$ .

It should be noted that the transmission factors given in Fig. 4 are for atmospheres which, as judged by visual inspection, may be characterized by the verbal description, clear. It is unlikely, however, that they apply precisely to an atmosphere which actually contains no condensed water vapor or dust. Since such a condition of perfect clarity is extremely rare, this is no disadvantage to the user of Fig. 4.

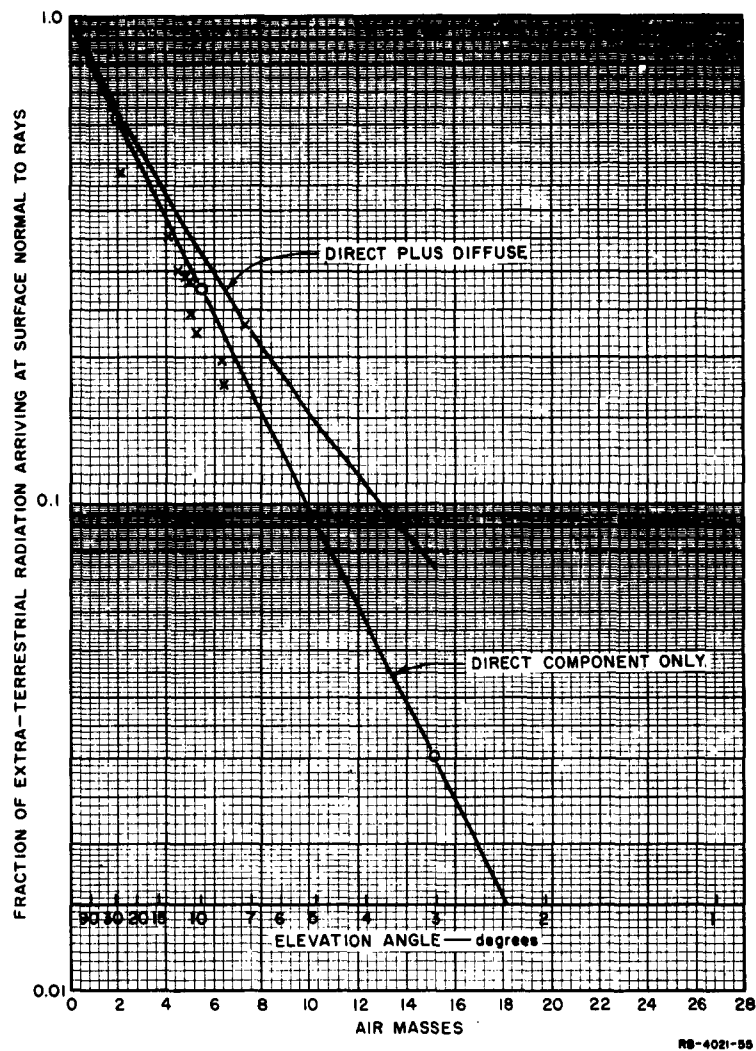


FIG. 4 ATMOSPHERIC ATTENUATION FACTORS FOR HIGH ALTITUDE NUCLEAR DETONATIONS AS A FUNCTION OF ELEVATION ANGLE OF THE RAY ABOVE THE HORIZONTAL FOR THE AVERAGE CLEAR DAY AT SEA LEVEL

It should be borne in mind when comparing other data with the curve in Fig. 4 that this curve is for the luminous energy arriving normal to the sun's rays at the earth's surface, and not the total solar spectrum.

In addition to the optical air mass, the related solar elevation angles (above the horizon) are given along the abscissa in Fig. 4. Note the very rapid variation in the transmissivity for changes from  $2^{\circ}$  to  $10^{\circ}$  in solar elevation angle compared with the variation from the entire  $80^{\circ}$  change from  $10^{\circ}$  to  $90^{\circ}$ .

The magnitude of the skylight or diffuse component shown in Fig. 4 are upper limits of those expected from nuclear detonations. Therefore, the proper values for nuclear detonations must lie between the curve for total radiation (that which includes both skylight and direct sunlight) and the attenuation curve for the direct component only.

Among the data found during the course of this investigation were some atmospheric turbidity reports published by McCormick.<sup>8</sup> (See Ref. II-A-2-e in Bibliography.) Using the original data sheets from which the turbidity reports were prepared, the percent of extra-terrestrial radiation reaching the earth's surface at the wavelength 5000A was computed for several clear days in Cincinnati, Ohio (see crosses in Fig. 4). Since 5000A is near the 50% point on the standard visibility curve, these transmission factors should compare well with the curve for transmission of the direct solar component in Fig. 4. As can be seen, the crosses cluster about the curve, showing reasonable agreement between the two sets of data. This general agreement suggests that the turbidity reports might be of great value in determining atmospheric transmission on cloudless days. Measurements of atmospheric turbidity have been made on days with clouds no closer than several tens of degrees from the sun at each of some 30 United States weather stations since August 1961. Hence, these data represent a continuing source of information on atmospheric transmission at 5000A.

The attenuation estimates from the Volz sun photometer measurements at 5000A (the basis of the turbidity reports) underestimate the transmission because the diffuse component of radiation is not measured. It may be possible to correct this transmission data using some of the

information presented by Gibbons.<sup>9</sup> For example, in Fig. 13 of Ref. 9, one sees that for radiation of 0.50 micron (5000A) wavelength and a distance at which direct component is reduced to one-tenth its free space value, the transmission of the total radiation (direct and diffuse) is three times that for the direct component alone. Equation 3 is an approximate formula given by Gibbons<sup>9</sup> for the ratio of the total to the direct component transmission.

$$\frac{T_{\text{total}}}{T_{\text{direct}}} = 1 + 0.74 \sigma D \quad (3)$$

where

$T_{\text{total}}$  is the transmission of the radiation including both direct and diffuse components,

$D$  is the path length (through the hazy part of the atmosphere where  $\sigma$  describes the attenuation) in km if path length  $< 11$  km or  $D = 11$  if path length is  $> 11$  km,

$\sigma$  is the attenuation coefficient  $\text{km}^{-1}$ .

The measurements on which Equation 3 is based were made in the San Francisco Bay Area over sea level paths up to 23 km in length. When applying Gibbons' data to very high altitude nuclear detonations, only that part of the path through the atmosphere which passes through the haze layer near the ground may be considered when determining the value of  $D$ . Thus if a uniform haze layer had a thickness from ground of about 1 km and the rays were passing through 10 optical air masses, the effective path length through the haze would be 10 km.

The value of  $\sigma$  in Equation 3 can often be derived from weather data by assuming that the limits of visibility are that distance over which the direct component of radiation at the peak of the standard visibility curve (0.556 micron) has been attenuated to the value 0.02; namely, that

$$\sigma = \frac{3.91}{V} \quad (4)$$

where  $V$  is the visibility in kilometers. The usefulness of this assumption

depends entirely on the degree of correlation between visual observations of the limits of visibility and the quantitative definition that has been generally accepted, i.e., an attenuation to 2% of the original intensity. That degree of correlation is likely to be highly dependent on the skill of the observer if a standard visibility instrument is not in use.

#### B. Clouded Atmospheres

There appear to be two major experimental studies of the effect of clouds on sunlight. One gives the results of measurements of the entire solar energy spectrum to a horizontal surface as a function of thickness of California coastal stratus clouds.<sup>10</sup> The other considers primarily the luminous flux transmitted through layers of clouds, the clouds being described in qualitative terms such that they might be judged or estimated by an observer without instruments other than the human eye.<sup>2</sup>

Even though different parts of the solar spectrum were treated in these two studies, they may be considered together (Fig. 5) because fogs or clouds are not strongly wavelength dependent in their attenuation. For example, stable fogs have an optical density that is practically uniform from 0.35 micron to about 3 microns wavelength.<sup>11</sup>

The effect of solar elevation angle on the data of Fig. 5 should be noted. Neiburger<sup>10</sup> did not state the solar elevation for the measurements reported. Hence, these cannot be corrected to differently oriented surfaces. (In general, transmission to a horizontal surface is greater than that to an optimally oriented surface and so will be an upper limit.) Data in Reference 2 are given in terms of verbal descriptions of cloud cover, which the authors claim automatically corrects for solar elevation angle differences. For example, a cloud layer that would appear in the category medium cloud for sun near the zenith might appear in the category heavy cloud with the sun near the horizon.

The abscissa of Fig. 5 applies only to the experimental points shown on the curve which are from the measurements of Neiburger and to the vertical bars from calculations of Hewson.<sup>12</sup> Shown in the same figure for convenience are the verbal descriptions of cloudiness given in Reference 2 with arrows pointing to the attenuation expected for each

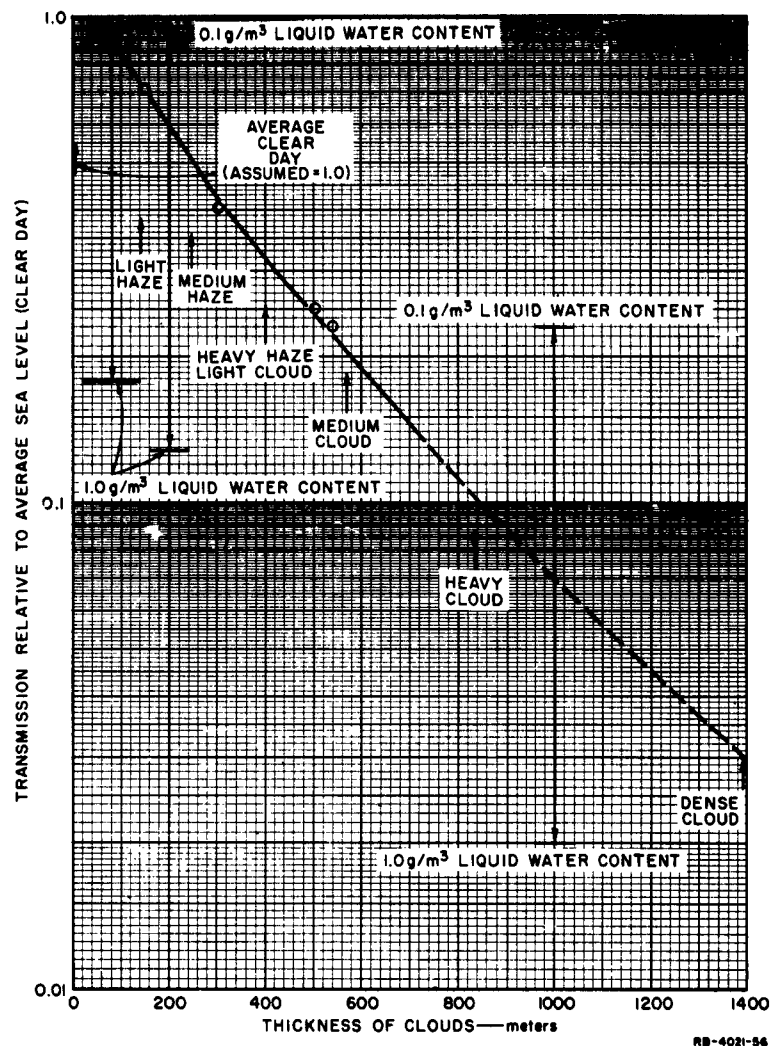


FIG. 5 ATMOSPHERIC ATTENUATION FACTORS FOR HIGH ALTITUDE NUCLEAR DETONATIONS AS A FUNCTION OF CLOUD THICKNESS AND/OR CLOUD DENSITY AS VISUALLY JUDGED

cloudiness condition. The points for medium, heavy, and dense cloudiness are not meant to imply that the verbal descriptions of cloudiness correspond to any definite cloud thickness. Detailed descriptions of the verbal terms of Jones and Condit<sup>2</sup> are given in the appendix.

It should be mentioned that the attenuation scale is relative to the average clear day at sea level and not relative to the extra-terrestrial radiation level. Thus, the transmission factor determined from Fig. 5 should be multiplied by the transmission factor determined from Fig. 4 to get an overall transmission factor for radiation coming from a very high altitude nuclear detonation or the sun.

As pointed out by Neiburger,<sup>10</sup> most of the theoretical studies of effects of clouds on radiation have assumed the clouds to be homogeneous in drop size of the liquid water and numerical volume concentration of drops. However, measurements of the liquid content made in typical California stratus<sup>10</sup> show that as one proceeds from the bottom towards the top of the cloud layer of these types, the liquid water content increases monotonically from around 0.1 gram/m<sup>3</sup> to around 0.5 gram/m<sup>3</sup>. Thus, Neiburger<sup>10</sup> proposes that discrepancies between experimental results and some of the theoretical studies resulted from the nonhomogeneity of the cloud layers studied.

Of course, not all clouds that occur are identical to the California coastal stratus. The effect of variations in the liquid content and the droplet size of clouds is shown by the results of a theoretical calculation by Hewson.<sup>12</sup> Hewson also found from his theoretical calculations that the transmission, reflection, and absorption in clouds was relatively independent of the solar elevation angle if transmission is defined for a horizontal surface both above and below the cloud. Notice in Table II (from Hewson<sup>12</sup>) the very large variation in transmission for even cloud thicknesses of 20 meters when the liquid water content of the cloud is varied between 0.1 and 5 grams/m<sup>3</sup>. Variations due to the size of the droplets are also evident, the smaller drop sizes giving the smaller values of the transmission. Twenty-micron droplet size is more or less characteristic of coastal fogs and 5-micron droplet radii are more or less characteristic of cumulus clouds found in continental climates.



Table II  
TRANSMISSION OF SOLAR RADIATION TO A HORIZONTAL SURFACE THROUGH CLOUDS  
OF VARIOUS THICKNESSES\*<sup>12</sup>  
(elevation angle = 65°)

Cloud Thickness (meters)	Droplet Radius (microns, $\mu$ )		Cloud Liquid Water Content (grams/m <sup>3</sup> )	Transmission %	
				20 $\mu$ Drops	5 $\mu$ Drops
20	20	5	0.1	98.5	93.4
20	20	5	1.0	86.6	61.5
20	20	5	5.0	55.8	23.9
80	20	5	0.1	93.8	81
80	20	5	1.0	61.5	18.5
90	20	5	5.0	22.9	6.2
200	20	5	0.1	86.6	61.5
200	20	5	1.0	38.4	13.1
200	20	5	5.0	9.1	2.3
1000		5	0.1		23.9
1000		5	1.0		2.3
1000		5	5.0		0.5
4000		5	0.1		0.2
4000		5	1.0		0.5
4000		5	5.0		0.1

\* Source: These data are from Table I of Reference 12.

From Table II and Fig. 5 it is readily understandable why such a wide variation of experimental values have been obtained by various investigators measuring solar radiation transmission through clouds. In most experiments the droplet size and the cloud thicknesses are not measured.

Comparing Table II with Fig. 5, it would appear that the dense cloud given in Fig. 5 would correspond to two possible types of clouds. The first might be a cloud of 5-micron droplets, 200 meters in thickness, with a liquid water content of 5 grams/m<sup>3</sup>, or a 1000-meter thick cloud of 5-micron droplets with a liquid water content of 1 gram/m<sup>3</sup>.

Of peripheral interest in the work of Hewson<sup>12</sup> is his computation of the energy absorbed by the cloud. The largest absorbed component was about 10% of the total incident energy and this occurred for a cloud

200-meters thick composed of 20-micron droplets and having 5 grams/m<sup>3</sup> liquid water content. In general, the fraction absorbed is negligible compared with that which is reflected and transmitted.

Haurwitz<sup>13</sup> has approached the cloud obscuration of total solar energy in a somewhat different way. He has attempted to deduce the relation between the transmission to a horizontal surface and the type of cloud as recorded by various weather stations, in particular the one at Blue Hill Observatory in Massachusetts. His study was confined to times of 100% overcast during the eight years from 1938 to 1945. Since his results were determined for a horizontal surface only, the summary of results in Table 4 (Reference 13) has been adjusted by correcting them to the percent transmission that would be observed by a surface normal to the sun's rays (Table III). A normal surface under cloudy conditions would receive about the same amount of radiation as a horizontal one. Under a cloudless condition it would receive an amount of energy equal to cosecant E times that received by the horizontal surface where E is the solar elevation angle. Table III has the advantage that common daily weather observations can be used to make reasonable estimates of the transmission for a given sky condition.

Table III

TRANSMISSION OF SOLAR ENERGY THROUGH VARIOUS TYPES OF CLOUDS TO A SURFACE NORMAL TO THE SUN'S RAYS FOR OPTICAL AIR MASSES FROM 1.1 TO 5.0 (after Haurwitz\*\*<sup>13</sup>)

Solar Elev. Angle (°)	Air Masses No.	Cloud Type					
		(Transmission % of that received from cloudless sky)					
		Alto-Cumulus	Alto-Stratus	Strato-Cumulus	Stratus	Nimbo-Stratus	Fog
65	1.1	47(40)*	37(32)	32(28)	23(20)	14(12)	14(13)
30	2.0	25(17)	20(13)	17(11)	12(8)	10(7)	9(6)
19	3.0	16(10)	14(8)	11(7)	8(5)	8(5)	6(4)
14	4.0	11(6)	10(6)	8(5)			4(2)
11	5.0			6(3)			4(2)

\* The values in parentheses are corrected to account approximately for the part of the hemisphere not seen by the optimally oriented surface under overcast conditions.

\*\* These data were derived from Table 4 of Reference 13.

One important observation that can be made from Table III is that a very definite effect seems to be evident from variations in the solar elevation angle or air mass. Such a variation does not appear when data are plotted only with regard to the transmission to a horizontal surface. In Fig. 5 Jones and Condit's transmission values were defined in terms of the appearance of the sky, which automatically adjusts to changes in solar elevation by a change in the visually adjusted degree of cloudiness. Neiburger's results shown in Fig. 4 could not be corrected for solar elevation angle because that variable was not given for the observations reported. The pyrheliometers used by Neiburger were both oriented horizontally and hence his transmission values are upper limits to those for an optimally oriented surface.

One additional point regarding Table III should be mentioned. The correction of Haurwitz's<sup>13</sup> data to the transmission factor for a surface normal to the sun's rays assumed an omnidirectional distribution of energy arriving at the ground during the overcast condition (that is, for example, a vertical surface would be assumed to receive the same flux as a horizontal one). This assumption ignores the fact that the vertical surface is exposed to only half the upper atmosphere. Thus, the additional factor applied in the adjustment of the data from Table 4 of Haurwitz<sup>13</sup> was  $[(\pi/2)+E]/\pi$  to correct the energy received under overcast conditions for the reduction in the fraction of the total hemisphere seen by the receiver oriented normal to the sun's rays. The numbers in parentheses in Table III are those to which this additional correction  $[(\pi/2)+E]/\pi$  has been applied. (E is the local source elevation angle.)

In summary, thermal energy transmission data through clouds to horizontal surfaces represent upper limits to the transmission factor appropriate for an optimally oriented surface. When the source elevation angle, E, is known, transmission factors for a surface normal to the direct rays can be derived by multiplying the horizontal surface transmission factors by  $(\sin E)[(\pi/2)+E]/\pi$ .

### C. Possible Approaches for Improving Estimates of Atmospheric Transmission

For many purposes, the information already presented can provide bases for estimates of thermal radiation from nuclear detonations at high altitudes. However, as more and more accurate estimates are demanded in a given situation, more detailed knowledge must be acquired of the atmospheric path along which the radiation must travel. One is therefore led to the question, "Can we improve our estimates of atmospheric transmission from a more extensive or wiser use of the data on the atmosphere we now have from meteorological weather stations?" "If so, precisely what data should be sought in this quest?"

Since clouds of water droplets are the most effective of the common attenuating constituents of the atmosphere, the first efforts should be applied toward improvements in estimating transmission of a given cloud layer. One approach to this problem is to attempt to obtain cloud thicknesses from radiosonde (now often called radiosowind) data on relative humidity as a function of altitude.

Since the presence of cloud is associated with a relative humidity significantly higher than that of the regions free of clouds,<sup>14</sup> radiosonde records could be searched first for those days when a cloud layer is known to have existed, with a significant rise in relative humidity to be expected as the radiosonde reached the altitude of the observed cloud ceiling, dropping again when it emerged from the cloud top.

Balloon-borne radiosondes are sent aloft at numerous weather stations in the United States from which one may obtain a continuous record versus altitude of the temperature, relative humidity, and wind speed. The punched card data that are available provide values of the relative humidity and other variables at approximately 500-meter intervals of altitude which is insufficiently frequent to give an accurate picture of the thickness of cloud layers. However, the original data (continuous with altitude), can be obtained on microfilm.<sup>15</sup>

The obvious first correlation to attempt is one between cloud thickness and the solar energy measured simultaneously at the same station. It is expected that similar thicknesses of very differently constituted clouds will show very different transmission factors.<sup>12</sup> However, it

may be possible to distinguish between different types of cloud by other means and with this additional factor, to predict more reliably the transmission properties of a given overcast sky.

Another approach aimed toward improving estimates of the transmission of radiant energy by clouds is the development of additional measuring devices to be sent aloft routinely with the radiosonde. Of particular interest would be an instrument which could measure the fundamental quantities that describe a given cloud, namely, droplet size and droplet concentration. If this data were regularly available at weather stations where solar radiation was simultaneously recorded, the observed solar transmission could be compared with a detailed theoretical calculation based upon first principles. The feasibility of the development of such instruments should be investigated further.

#### IV IGNITION RADII FOR 100, 1000, and 10,000 MEGATON DETONATIONS ABOVE 50 km ALTITUDE

Figure 6 shows the number of calories per square centimeter at ground zero as a function of yield and the altitude at which the detonation occurs (neglecting atmospheric attenuation between 0.31 and 1.9 microns wavelength). Two curves are given for each of three energy fluxes: the dotted curves for the delivery of the stated energy flux within one second after detonation, and the solid curve for the delivery of that energy flux within 10 seconds after the detonation.

Having once determined the energy flux arriving at ground zero, the energy flux arriving at points away from ground zero can be computed using Fig. 7. Figure 7 shows the relative decrease in energy flux for various distances from ground zero.

Figures 6 and 7 assume the atmospheric transmission to be 100%; thus, they must be corrected. The proper correction factor for the average clear day at sea level may be obtained for any given ground point from Fig. 4. However, the elevation angle of the source as seen from the ground point must first be determined. This is straightforward for spherical fireballs.

The elevation angles for ground points under a pancake-shaped fireball can be assumed to be those for the center of the pancake, except within a circle of radius  $(h-80)/2$  around ground zero itself. The center of the pancake is always directly below the burst at the 80-km level. Within the radius  $(h-80)/2$  of ground zero the elevation angle is given approximately by the equation

$$E = \tan^{-1} \frac{160}{(h-80)} \quad (5)$$

Two examples of calculated ignition radii for each of three different sized nuclear detonations as a function of altitude of detonation are shown in Figs. 8 and 9. The three yields are 100, 1000, and 10,000 megatons. Radii were computed for materials requiring 25 or 10 cal/cm<sup>2</sup> in one second, respectively, for ignition.

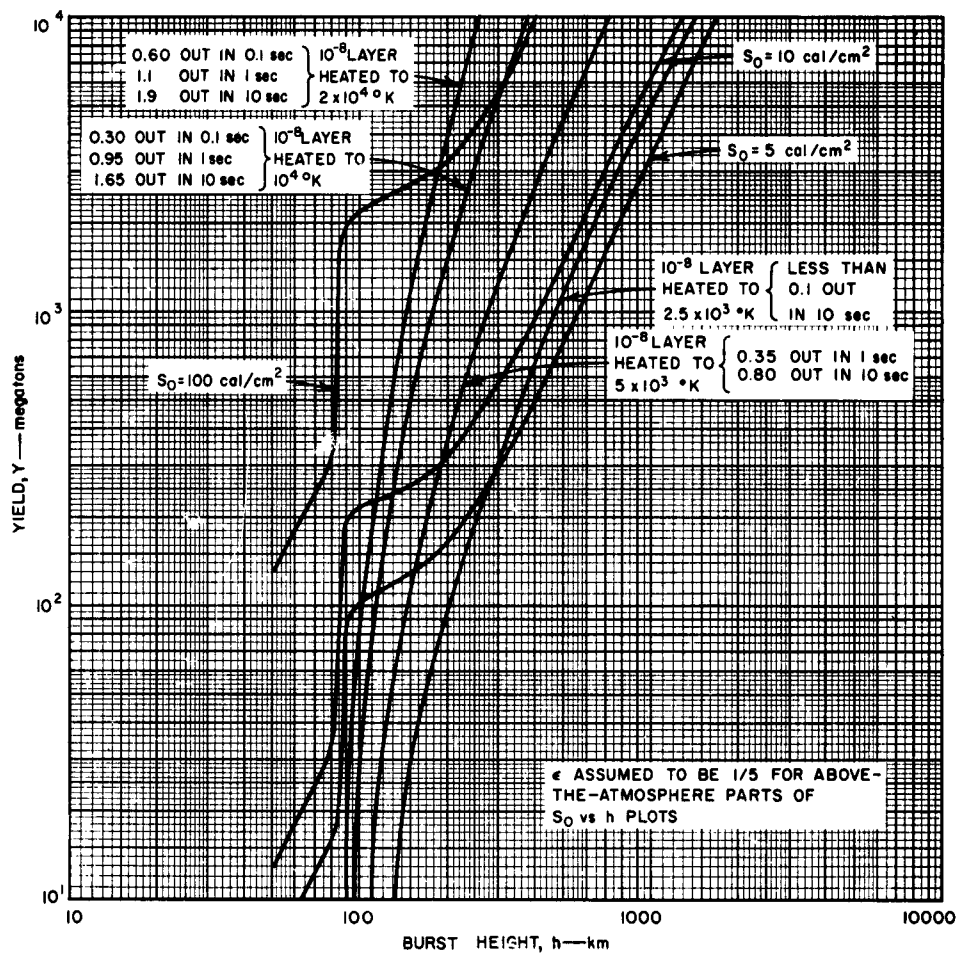


FIG. 6 YIELD REQUIRED TO DELIVER SPECIFIED THERMAL FLUXES AT GROUND ZERO WITHIN 1 sec OR 10 sec (atmospheric attenuation neglected)

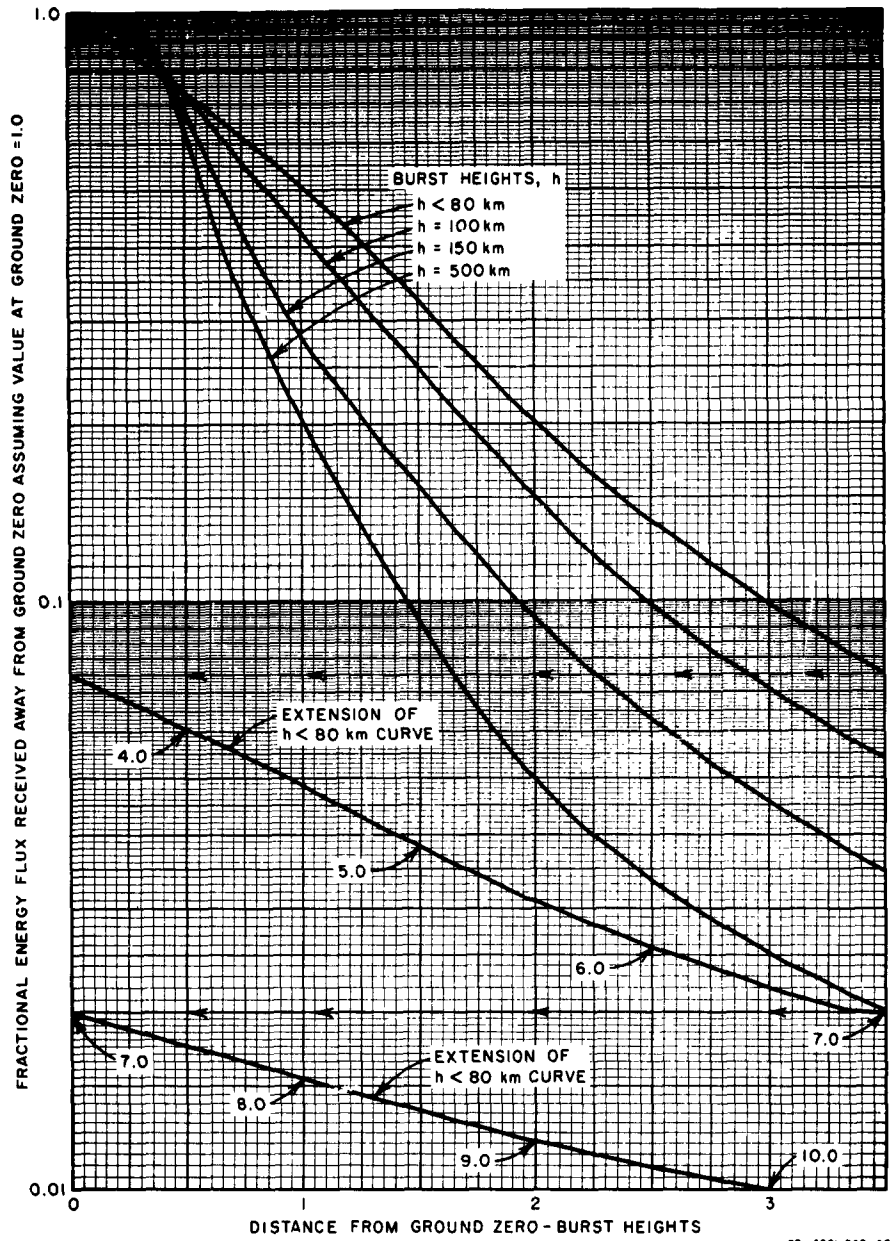


FIG. 7 THE RELATIVE ENERGY FLUXES ARRIVING AT OPTIMALLY ORIENTED SURFACES AT VARIOUS DISTANCE FROM GROUND ZERO (atmospheric attenuation neglected)



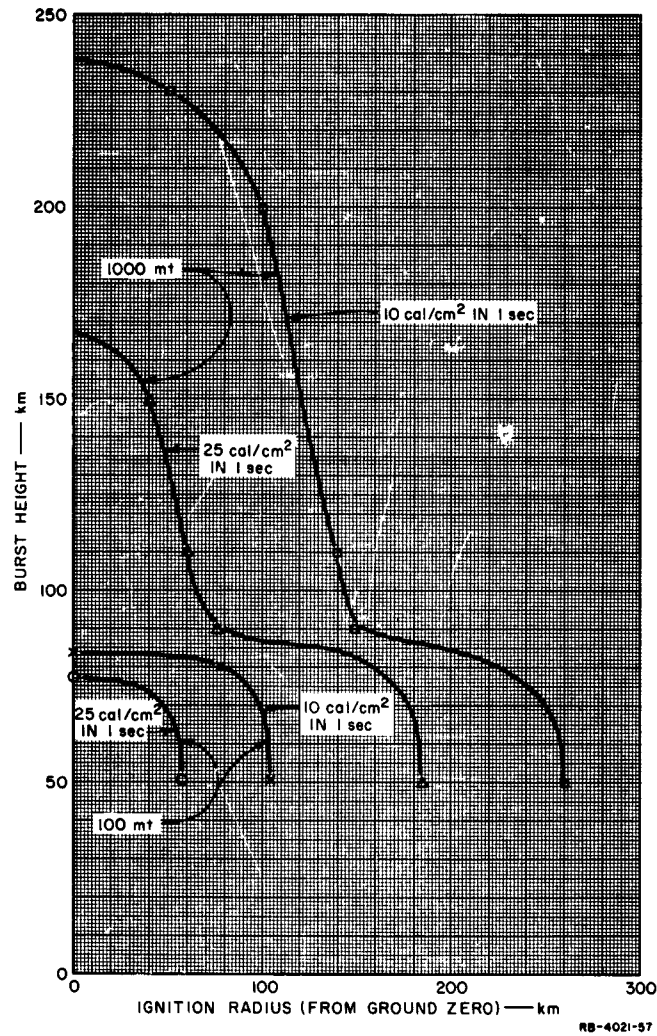


FIG. 8 TWO IGNITION RADII AS A FUNCTION OF BURST HEIGHT FOR 100 AND 1000 mt ON THE AVERAGE CLEAR DAY AT SEA LEVEL

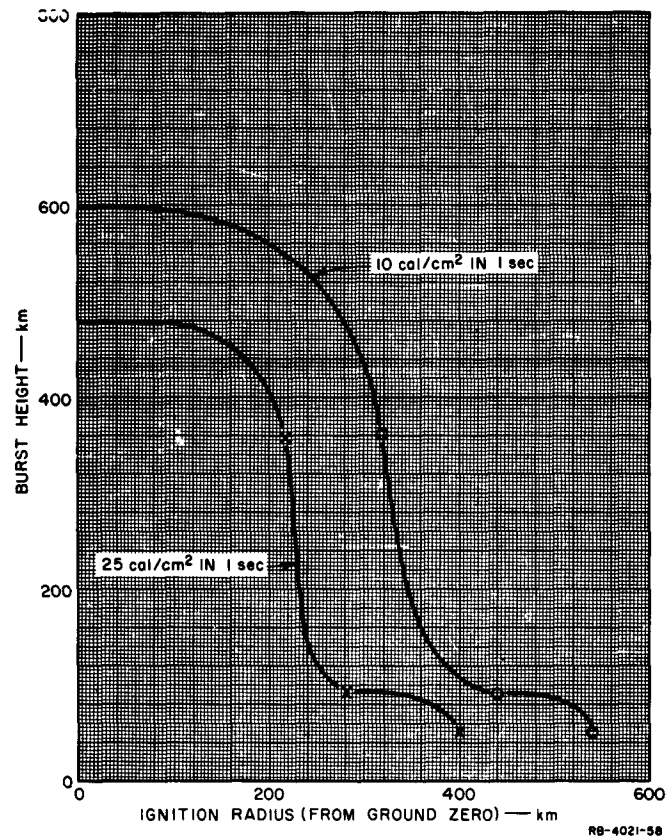


FIG. 9 TWO IGNITION RADII AS A FUNCTION OF BURST HEIGHT FOR A 10,000-mt NUCLEAR DETONATION ON THE AVERAGE CLEAR DAY AT SEA LEVEL

Having obtained such radii for the average clear day, they can be directly scaled to accommodate atmospheric conditions of varying cloudiness. For example, if there existed a cloud layer with a transmission factor of 10% (as for what is called heavy cloud, see Fig. 5), then the 10-calorie radius would automatically be considered the distance from ground zero within which greater than 1 cal/cm<sup>2</sup> would be received in one second after the burst.

It is well to orient oneself regarding these thermal fluxes by recalling that direct sunlight provides about 0.03 cal/cm<sup>2</sup>-sec. Thus, 1 cal/cm<sup>2</sup>-sec provides a flash some 30 times the intensity of the sun at the zenith on an exceptionally clear day.

Figures 10 and 11 show how the energy flux varies as a function of distance from ground zero for the detonation yields and altitude range considered in Fig. 8. The use of Figs. 10 and 11 allows the calculation of radii based on any energy flux (above 10 cal/cm<sup>2</sup>-sec) received on an optimally oriented surface up to the maximum available from a particular detonation on the average clear day.

It is generally recommended that in the use of Fig. 5 for calculating the attenuations due to cloud cover, that the elevation angle of the rays from the detonation to the ground point in question not be considered. On the other hand, if the cloud cover descriptions of Table III are used, the elevation angle is of obvious importance and must be separately computed for each point away from ground zero.

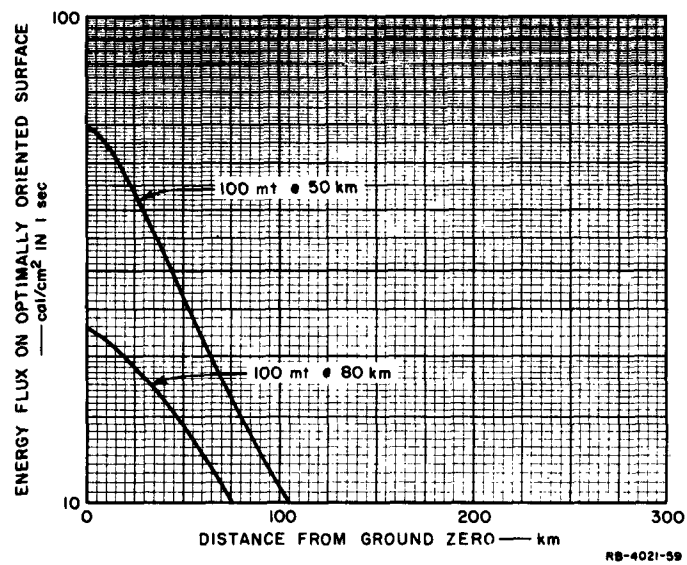


FIG. 10 THE ENERGY FLUX ARRIVING IN 1 sec ON AN OPTIMALLY ORIENTED SURFACE FROM A 100-mt DETONATION AT 50 km AND AT 80 km ALTITUDE, AS A FUNCTION OF DISTANCE FROM GROUND ZERO ON THE AVERAGE CLEAR DAY AT SEA LEVEL

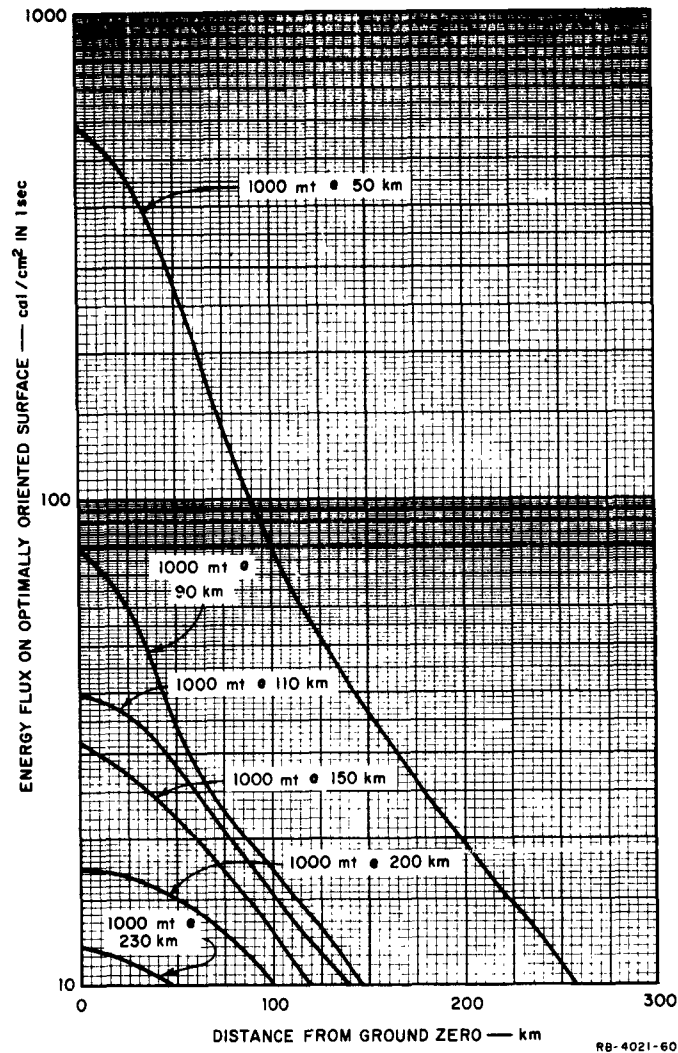


FIG. 11 ENERGY FLUXES (in 1 sec) AS A FUNCTION OF DISTANCE FROM GROUND ZERO FOR A 1000-kt DETONATION (at the altitudes 50, 90, 110, 150, 200, and 230 km) ARRIVING AT AN OPTIMALLY ORIENTED SURFACE ON THE AVERAGE CLEAR DAY AT SEA LEVEL

## V CONCLUSIONS

Sufficient experimental solar energy transmission data exists for an "average" clear day at sea level to give estimates of atmospheric transmission for high altitude nuclear detonations which are reliable to within +30% of the transmission factor.

Empirically derived graphs (such as Figs. 4 and 5) can be used for estimating atmospheric transmission under various common atmospheric conditions of haze, fog, and cloud. More precise empirical correlations of cloudiness and solar energy transmission can probably be derived from data currently collected by the United States Weather Bureau.

Much of the available solar transmission data from the U.S. Weather Bureau for cloud cover gives the transmission to a horizontal surface for many different solar elevation angles. An approximate correction of these transmission values to those for an optimally oriented surface (normal to the direct rays) is accomplished by multiplying horizontal surface transmissions by the factor  $(\sin E)[(\pi/2)+E]/\pi$ .

Atmospheric turbidity reports<sup>8</sup> based on measurements with the Volz sun photometer are a continuing source of information the atmospheric attenuation factor (direct component only) for radiation at 5000A on cloudless days. These data have been obtained at some 30 stations in the United States since about August 1961.

The more accurate description of atmospheric variables is of greater importance than development of more accurate numerical procedures. Numerical procedures have already been worked out (see I-A-1 and I-A-2 in Bibliography) to handle the primary variables in this complex problem for unclouded days which are: (1) scattering by haze particles, (2) reflection from boundary surfaces, such as the earth's surface, and (3) selective absorption of energy by water vapor. The prime difficulty in the use of these procedures for any practical situation is the detailed description of the atmospheric variables, particularly the size and concentration of liquid and solid particles.

Theoretically estimated upper limits to the unattenuated energy flux from a 1000-mt detonation (taken from Reference 1) combined with

empirical estimates of atmospheric transmission, give ignition radii ranging from 250 km at 50-km burst height to zero km at 240-km burst height for the average clear day at sea level.

#### Recommendations for Future Research

The general and specific uses of atmospheric transmission measurements should be delineated within the framework of the overall civil defense program. For example, information should be available on how the Office of Civil Defense could use instantaneous atmospheric transmission data from important localities. Once the need for this information is established, the following recommended research is appropriate.

It has become apparent in this study that additional effort might be profitably expended to allow more reliable estimates of atmospheric transmission. Two main directions for this effort are: (1) improvement in the use of presently available information on the atmosphere, (2) development of instrumentation which makes possible the routine collection of additional data of importance to this problem. The following possible approaches are proposed as a beginning.

Means for better routine measurement of the transmission properties of clouds should be sought because variations of cloudiness cause greater fluctuations in transmission than almost any other atmospheric constituent. During daylight hours the continuous record of insolation monitors the transmission for rays at the elevation angle of the sun. However at night, one must rely on less directly analogous measurements. For example, cloud thicknesses may possibly be derived from current radiosonde records of relative humidity as a function of altitude. A study should be made of the possibility of using cloud thickness to predict transmission. Also, development and routine use of instruments for measuring droplet size and concentration in clouds as a function of altitude would give more fundamental data from which the transmission could be computed.

To obtain transmission factors for hazy atmospheres common to industrial centers, the Volz sun photometer data currently being collected<sup>15</sup> should be tapped as a continuously available measure of the scattering coefficient of the atmosphere at a wavelength (0.5 micron) of

great importance to transmission of radiation from high-altitude nuclear detonations. The above determined scattering coefficient should be used in combination with the experimental results of Gibbons<sup>9</sup> on the ratio of direct plus diffuse to direct transmission. The eventual goal of this combination of experimental data would be the derivation of a table of "build-up" factors similar to those of gamma-ray transmission through solids. Thus, the transmission of the atmosphere would be the transmission of the direct component of the radiation multiplied by a build-up factor that corrects for the transmission via the diffuse or indirect component. These tables could be checked by an experimental program which measured the 5000A component of solar energy over the entire upper hemisphere at the same instant the collimated receiver was in operation. This would give corroboration of the upper limit on the build-up factor since the sun's indirect or diffuse component is expected to be somewhat greater than that of a nuclear detonation at high altitude.

A system to monitor the transmission of all atmospheres when the sun is below the horizon should be sought. One possibility to explore is the placement of an intense flashing light aboard a near earth satellite. If the study of clouds were to be emphasized, a ruby laser (at 6940A) might be considered for the light source. Filtered detectors on the ground accepting  $2\pi$  steradians would give the basic data for transmission calculations. Another possibility (again oriented towards measurements for cloudy conditions) is an entirely ground-based system for measuring the albedo of cloud or haze layers. An intense pulsed light source (such as a ruby laser) would be directed upward at various angles. The signals obtained on an array of  $2\pi$  detectors on the ground would allow calculation of the albedo or reflectivity of the cloud layer. The use of such a system assumes the albedo for upward going radiation does not differ significantly from that of descending radiation.



## Appendix A

### EXPLANATION OF VERBAL DESCRIPTIONS OF CLOUD COVER

Quoting directly from pages 174 and 175 of Jones and Condit:<sup>2</sup>

"Clear - High purity of the blue sky color, general low level of sky luminance, cast shadows sharp, dark and distinct.

"Light Haze - Sky color white of high luminance, almost dazzling near the sun, producing a feeling of glare and visual discomfort. Cast shadows visible but more grayish than for clear condition.

"Medium Haze - Sky near sun white but not dazzling. General appearance - bright grayish white. Sun's disc may be viewed directly without serious visual discomfort, cast shadows visible but faint, of low contrast and soft appearance.

"Heavy Haze - Sun's disc only a few times more luminous than the immediate surrounding sky; sky a dull graying white, cast shadows barely visible.

"Light Cloud - Sun's disc invisible or intermittently so, sky as a whole light gray with maximum luminance in the immediate vicinity of the sun's position, no cast shadows.

"Medium Cloud - Sky as a whole dull gray with maximum luminance at the zenith, not near the sun's position which cannot be determined by visual inspection. Sky luminance diminishes gradually in all directions from the zenith to about 1/4 of the zenith value near the horizon.

"Heavy Cloud - Sky dark gray with maximum luminance at the zenith but very little if any perceptual decrease of luminance toward the horizon, position of the sun indeterminate.

"Dense Cloud - Sky in general has a very dark gray gloomy appearance with no perceptual luminance gradient from zenith to horizon. This condition produces conscious feeling of low luminance level usually associated with dusk and dawn conditions."

The above description of Jones and Condit of sky conditions is in general applicable to uniform cloud cover. However, on many occasions it is necessary to deal with clouds which show marked, striated, and mottled non-uniformities and also with a sky more or less filled with detached cloud masses varying greatly in shape, size, and position. Jones and Condit<sup>2</sup> recommend that the appearance of the sun and the sky immediately around the sun is still the best criterion of the available luminous density and therefore the transmission of solar energy by the atmosphere. Thus, if the sky is partially filled with cloud masses so broken that the sun is unobscured and the sky around it is of clear deep blue, and if the rift in the clouds is of sufficient size, then the luminous transmission is very nearly the same as for a clear atmospheric condition for the same solar elevation angle. On occasion, the bright cloud masses away from the sun may actually increase the total energy arriving at a given point up to 30% above that received from a cloudless sky. The reader is referred to the original paper by Jones and Condit<sup>2</sup> for more details of judging the opacity of cloud cover.

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## AN ANNOTATED BIBLIOGRAPHY

This bibliography gives a brief resume of the papers and reports that contain useful information for solving the general problem of the attenuation of thermal radiation by the earth's atmosphere. The first set of papers treated are those which were oriented directly toward the problem at hand; namely, the transmission of thermal radiation from nuclear weapons. However, after these relatively few papers are discussed, a much larger number of papers regarding the transmission of the sun's energy through the earth's atmosphere are reviewed.

Intensive study of the sun has been going on for over fifty years, particularly at the Smithsonian Institution and the U.S. Weather Bureau. Since the wavelengths of sunlight are not very different from those emitted from nuclear weapons detonations, much of the data collected on the sun applies directly to transmission of thermal radiation from nuclear detonations. This is especially true for a very high-altitude nuclear detonation which irradiates the top of the earth's atmosphere quite uniformly as does the sun. Hence, the diffuse or indirectly transmitted component for sunlight, though greater, is not very different from the indirect or diffuse component of transmitted energy from a very high altitude nuclear burst. Some of the papers to be discussed are more oriented toward the nuclear detonation within the atmosphere; namely, under 10-km altitude. These will be included for completeness even though our emphasis is for detonations above 50 km.

The papers discussed below are grouped according to the following outline:

- I. General Papers Directly Concerned with Nuclear Detonations
  - A. Theoretical
  - B. Experimental
- II. Studies of Solar Energy Transmission through the Earth's Atmosphere
  - A. Relatively Clear Atmospheres
    - 1. Theoretical
    - 2. Experimental
  - B. Cloudy Atmospheres
    - 1. Theoretical
    - 2. Experimental

## I. General Papers Directly Concerned with Nuclear Detonations

### A. Theoretical

1. Cahill, John P., Hervey P. Gauvin, and John C. Johnson.  
Effective Transmission of Thermal Radiation from Nuclear  
Detonations in Real Atmospheres, Air Force Surveys in  
Geophysics, No. 144 (April 1962)

This report is probably the most complete and usable report on this subject of any that have been discovered by the author. The results are presented as the ratio of the irradiance received on a  $2\pi$  detector (flat plate) in the presence of an attenuating atmosphere to the irradiance expected on the same detector in free space. Although high altitude nuclear detonations are not specifically excluded, the report emphasizes the altitude range under 10 km. The primary factors that are considered in the report are: (1) scattering and absorbing properties of the atmosphere, (2) reflection from the underlying ground surface, (3) the temperature-time characteristics of the source, (4) the source detector geometry.

The report considers only cloudless atmospheres with varying degrees of haziness, namely, visual ranges or visibilities of 3.2, 16, and 80 km. Ground reflectivities of 0.0, 0.2, and 1 were considered, as well as humid tropic atmospheres and dry continental atmospheres. Twenty different computed examples are shown graphically for the transmission factor from detonations at 0, 1.5, and 9 km out to both vertical and horizontal ranges of 30 km from ground zero. The following general conclusions are of particular importance:

- (1) The most sensitive parameter determining the transmission factor was scattering by atmospheric haze particles.
- (2) Enhancement (by diffuse reflectance) of transmission due to haze was found in general to be small. In any case, it was not significantly different for the different possible assumptions that can be made regarding the particle size distribution and concentration with altitude.
- (3) The next factor of importance in determining the transmission was the albedo (reflectivity) of the diffusely reflecting earth.
- (4) The least important factor, at least at ranges where men and machines can survive the thermal load, is the difference in transmissivity due to different amounts of water vapor in the path between the detonation and a given point.

Thus, the primary cause for modification between the transmissivity of different atmospheres will be due to changes of the vertical distribution of the size and concentration of scattering particles. The author comments that "unfortunately, this parameter is the least precisely known and is not a routinely measured or even estimated meteorological parameter."

I. General Papers Directly Concerned with Nuclear Detonations  
A. Theoretical

Major assumptions in the report are: (1) no radiation need be considered outside the band of wavelengths between 0.32 and 3.57 microns, (2) the time characteristics are those of a nuclear detonation within the atmosphere, (3) the receiver of the radiation is assumed to be a flat plate, able to receive energy from the entire hemisphere or  $2\pi$  steradians of solid angle, (4) the receiver is optimally oriented, that is, oriented in such a way as to receive the greatest amount of energy from the nuclear detonation.

At 30-km range on the ground from ground zero some significant results of the detailed calculations for 1.5-km burst height are:

(1) For the clearest atmosphere considered (visibility 80 km) and ignoring differences in the quantity of water vapor, a change of albedo of the earth from 0.2 to 1 changes the transmission factor from 0.25 to 0.55;

(2) for an atmosphere of 16-km visibility, at a range of 15 km from ground zero, a change of albedo from 0.2 to 1 changes the transmission factor from 0.11 to 0.25;

(3) for an atmosphere with visibility 3.5 km and assumed albedo of 0 for the earth (it is usually 0.1 to 0.2), the transmission factor is reduced to 0.01 at a distance of only 10 km from ground zero.

These few examples illustrate the enormous effect of scattering due to haze particles and the important but secondary effect of the albedo or reflectivity of the earth.

The reason for the lack of sensitivity to the water vapor content of the atmosphere is due to the fact that the radiation that lies within the water vapor absorption bands is depleted from the beam in the first few kilometers from burst point, and thereafter, being depleted in that wavelength region, the beam attenuation is independent of water vapor concentration.

It is not clear whether the analytical approaches of this report can be used for significantly greater ranges or distances from the burst point than 30 km. While the report is very clear in giving mechanisms for making a given calculation, it is also quite clear that a very long and detailed effort must be made using a digital computer for any given calculation of transmissivity. In other words, the situation is sufficiently complex that the authors of the report did not give any simplified rules of thumb for calculating transmissions based on the results of their study.

2. Chin, J. H. and S. W. Churchill, Radiant Heat Transfer Through the Atmosphere, Chem. Eng. Prog., 56, Symposium Series No. 30, 117-127 (1960)

The difference between this paper and I-A-1 is in the manner of presentation. Identical factors and steps in calculating the transmissivity of the atmosphere were used in both. Both papers lean heavily

I. General Papers Directly Concerned with Nuclear Detonations  
A. Theoretical

upon experimental data regarding the scattering properties of haze particles. For example, the chief difference that this author could discover was the manner in which the two papers mathematically averaged over the sharp absorption bands of water vapor (which, in any case, has been shown to be a parameter to which the transmissivity is markedly insensitive). On the effects of haze, this paper relies heavily upon the basic Mie scattering theory; however, less guidance is given the user of their equations regarding common haze particle concentrations and size distribution with altitude than is found in I-A-1. In other words, with a detailed knowledge of the particle concentration and size distribution with altitude, one could more readily use the equations of this paper; but recognizing the lack of such data, paper I-A-1 shows reasonable assumptions that can usually be made.

This paper approximates the angular dependence of scattering by haze particles with a computation of the back-scattered fraction, and computes this fraction for various size particles relative to the wavelengths of the light under consideration. The model obtained is therefore called the two-flux approximation, which is claimed to yield a better representation for the intensity than the diffusion model (the latter is widely used in the essentially analogous problem of neutron scattering). The two-flux representation (the forward flux and the backward flux) gives an ordinary differential equation for the energy flux flowing from the detonation toward the point in question, and another ordinary differential equation for the flux returning towards the direction of the detonation. Both general and specific solutions for these two equations are given. The reflectivity of the ground is introduced into the equations by assuming it to be another source, that is, a plane parallel source providing two vertical components, one up and one down which are then added to the original two fluxes of the radiation flow. The primary conclusions that can be drawn from this report are: (1) a point source approximation is usually a reasonable representation of a finite spherical source for a typical atmosphere, (2) in spite of the fact that analytical solutions were obtained for this problem, to quote the authors, "Numerical calculations are necessarily tedious because of the large number of parameters and the inherent spectral and geometrical complexity."

The authors give only one illustrative example, a radiant source at 6000°K, detonated at 150-meters altitude, in an atmosphere having a visibility of 2.1 km and a ground surface with a diffuse albedo of 0.3. The only transmission value given is for a range of 0.75 km from the burst point where the calculated transmission factor is 0.70.

B. Experimental

1. Glasstone, S., editor, The Effects of Nuclear Weapons, revised edition, U.S. Atomic Energy Commission, April 1962, available from Superintendent of Documents, U.S. Govt. Printing Office, Washington 25, D.C.

I. General Papers Directly Concerned with Nuclear Detonation  
B. Experimental

Without giving the source of the information on transmissivity, a graph is shown on p.363 for the transmittance as a function of slant range between 10 and 42 km for two visibility ranges, 16 and 80 km. The claim is made that the transmission values are good out to distances of the order of half the visibility in each case. On p.367 is given a curve of transmittance more appropriate for very high altitude nuclear explosions for two atmosphere visibilities, one of 150 km and the other of 50 km. The set of values for 50 km is in fair agreement with some of the data that are discussed below from other sources for the so-called average clear day at sea level. This reference does not treat the atmospheric attenuation problem in depth.

2. Gibbons, M. G., J. R. Nichols, F. I. Laughridge, and R. L. Rudkin, Transmission and Scattering Properties of Nevada Desert Atmosphere, J. Opt. Soc. Am., 51, 633 (1961)

This paper by personnel at the U.S. Naval Radiological Defense Laboratory at San Francisco gives experimental data from a xenon flash lamp shining through the night sky of the Nevada desert towards a receiver that was placed at various locations from 0.8 to 21 km from the source. Of prime importance to our problem is their determination of the ratio of the energy arriving at a flat plate optimally oriented toward the source, and that which arrives at a highly collimated receiver of the same cross sectional area. This ratio was studied as a function of the wavelength of the light, namely, in four wavelength regions at 0.4, 0.5, 0.7, and 0.83 micron. Representative ratios at a distance of 21 km are 2.2, 2.0, 1.5, and 1.3 for the wavelengths 0.4, 0.5, 0.5, and 0.83 micron, respectively. Thus, at these ranges the direct plus diffuse transmission is as much as twice that for the direct component alone. Another important contribution of basic information in this paper is its publication of the angular dependence of haze scattering for the four wavelengths mentioned above. In this experimental study the effects of Rayleigh scattering could not be separately determined from those of the haze, but Rayleigh scattering is well known theoretically and can be subtracted.

3. Gibbons, M. G., F. I. Laughridge, J. R. Nichols, and N. A. Krause, Transmission and Scattering Properties of a Nevada Desert Atmosphere under Cloudy Conditions, Res. and Dev. Tech. Rpt. USNRDL-TR-461, DASA-1192, August 1960.

This paper has a slightly more detailed version of I-B-2, showing the effect of an overcast sky at 1.2-km altitude on the diffuse component of transmitted radiation.

4. Gibbons, M. G., Experimental Study of the Effect of Field of View on Transmission Measurements, J. Opt. Soc. Amer. 49, 702 (1959)

This paper is similar to I-B-2, except that it treats the scattering properties of the atmosphere around San Francisco Bay rather

I. General Papers Directly Concerned with Nuclear Detonation  
B. Experimental

than that of the Nevada desert. Distances from 2 to 23 km, between the xenon flash lamp source and the detector were studied for energy at five different wavelength regions, namely, 0.4, 0.5, 0.7, 0.83, and 0.90 micron. For fields of view at the receiver of from  $4^\circ$  of arc to  $58^\circ$  of arc (half-angle of the cone), it was found that as in the Nevada desert atmosphere, the ratio of "scattered in" (diffuse or indirect) radiation to direct radiation received from the source is greater the shorter the wavelength, and for distances up to about 11 km, this ratio is approximately proportional to the optical thickness (path length times attenuation coefficient) of the path. For source receiver distances greater than 11 km and a given attenuation coefficient, the ratio in question has been found to decrease slowly with increasing distance.

5. Gibbons, M. G., Experimental Study of the Effect of Field of View on Transmission Measurements, Report No. AFSWP-1078, May 16, 1958, Res. and Develop. Tech. Rpt., unclassified

This report is the slightly more detailed report form of I-B-4.

6. Stewart, H. S., and J. A. Curcio, The Influence of Field of View on Measurements of Atmospheric Transmission, J. Opt. Soc. Amer. 42, 801-805 (1952)

This study is similar to those of I-B-2, -3, -4, and -5 except that it was done earlier and for just two path lengths of 3.2 and 14.4 km, respectively, in the Chesapeake Bay area. For an uncollimated source, the results they obtained for any wavelength in the visible and near ultraviolet regions of the spectrum are represented approximately by the relation  $T_0 = T + 0.5(1-T)(1-e^{-\theta})$ , where  $T_0$  is the transmittance at a particular wavelength measured with an instrument having a field of view  $\theta$  radians in diameter, and  $T$  is the transmittance which would be obtained if unscattered light alone were accepted by the measuring equipment. The study was done as a function of wavelength in the wavelength region of 0.36 to 0.64 micron.

7. Curcio, J. A., G. L. Knestrick, and T. H. Cosden, Atmospheric Scattering in the Visible and Infrared, Naval Research Laboratory Report 5567, January 1961

The main contribution of this paper is experimental data on the scattering coefficient of commonly encountered aerosol distributions in the atmosphere as a function of the wavelength of the light being transmitted. Since haze or aerosols are the most important factor in non-cloudy atmospheres for determining the transmission, this basic data should be of great use in many calculations of transmissivity. The locale of the measurements was Chesapeake Bay.

Path lengths of 5.4 km and 16 km were studied. The period covered in the measurements extends from April 1959 to January 1960 and includes such meteorological conditions as light fog, various degrees of haze, and clear weather. The visibility ranges covered were from 5.4



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5.4 km to 96 km and the relative humidity varied from 36 to 100%. The light source was a xenon flash lamp. The scattering coefficient, as shown in Fig. 16 of this paper, is shown to vary as the negative 0.5 to the negative 1 power of the wavelength.

8. Knestrick, G. L., T. H. Cosden, and J. A. Curcio,  
Atmospheric Attenuation Coefficients in the Visible  
and Infrared, Naval Research Laboratory Report 5648 (1961)

This paper describes atmospheric spectral attenuation coefficients which have been measured in 10 narrow wavelength bands between 0.4 and 2.3 microns wavelength for a variety of weather conditions using two over water sea level paths of 5.5 and 16.3 km. Only collimated receiver measurements were made.

II. Studies of Solar Energy Transmission to the Earth through the Atmosphere

A. Relatively Clear Atmosphere

1. Theoretical

- a. Coulson, K. L., Characteristics of the Radiation  
Emerging from the Top of a Rayleigh Atmosphere. I.  
Intensity and Polarization, Planetary and Space Sci.  
1, 265 (1959)

This paper gives the basic data required to determine the intensity of scattered light from any point in the sky for a wide variety of surface albedos of the earth, and for a wide variety of angles of the sun relative to the horizontal at the earth. It is an exact calculation of the radiative transfer in the atmosphere where the only scattering mechanism is Rayleigh scattering.

- b. Coulson, K. L., Characteristics of the Radiation  
Emerging from the Top of a Rayleigh Atmosphere. II.  
Total Upward Flux and Albedo, *ibid.*, 1, 277-284 (1959)

This paper is an extension of paper II-A-1a, corresponding to the calculation of the total upward flux and the albedo for an atmosphere in which the only scattering is Rayleigh scattering. An interesting result of the calculation is that the integration with respect to wavelength over the solar spectrum gives a value of 7.6% for the albedo of the earth due to pure Rayleigh scattering in the atmosphere. Considering the absorption by ozone, the computed albedo of the ultra-clear atmosphere of the earth is reduced to 6.9%. This, of course, is exclusive of the albedo of the surface of the ground, and is for radiation having the spectral distribution of extra-terrestrial solar energy.

## II. Studies of Solar Energy Transmission

### A. Relatively Clear Atmosphere

- d. Ashburn, E. V., Isophote Charts for the Visible and Infrared Spectral Region of the Cloudless Day Sky, NAVORD Report 3357, NOTS 932, August 5, 1954

This report gives in graphical or chart form information almost identical to that given in Reference II-A-1c.

- e. Threlkeld, J. L. and R. C. Jordan, Direct Solar Radiation Available on Clear Days, Heating, Piping and Air Conditioning, 29, 135 (1957)

This paper is essentially an extension of the work of Moon (II-A-1f) using the best known available data. It applies only to the direct component of solar radiation arriving on clear days at the earth. The paper appears to give calculations for a greater variety of conditions than the previous work by Moon. One inconvenient feature is that the units used are Btu per hour per square foot. Four basic standard curves are presented to give the direct solar radiation at normal incidence to a surface at any hour of the day throughout the year, at the latitudes 30°N, 42°N, and 48°N. Curves are given for the transmission factor as a function of precipitable water for each of the three concentrations of dust particles, 0, 400, and 800 particles/cm<sup>3</sup>.

- f. Moon, P., Proposed Standard Radiation Curves for Engineering Use, J. Franklin Inst., 230, 583-617 (1940)

This paper is one of the most useful compilations of the transmission of the direct component of solar radiation that has appeared. Using the extensive data on water vapor absorption and the extensive pyrheliometric records collected by the Weather Bureau and the Smithsonian Institution, Moon derived a "best" curve for use on "average" clear days at sea level at various elevation angles.

### 2. Experimental

- a. Hourly Solar Radiation Data, National Weather Records Center, Grove Arcade Building, Asheville, N. Carolina

Some 46 or more stations in the United States provide hourly totals of the solar radiation, both direct and diffuse, arriving at a horizontal surface. Combined with this data is information of the following type: the day, the month, the year, the hour, the radiation in cal/cm<sup>2</sup>; the elevation of the sun at a point midway through the previous hour; the total extra-terrestrial radiation on a horizontal surface; the number of minutes of sunshine in the hour to come beyond the hour listed; the fractional snow cover; the solar week; the opacity of the sky in tenths (that is, 10 means complete overcast, and 0 means clear); the solar hour (that is, the time as determined by the sun's position); the percent of possible radiation arriving at the ground (namely, that fraction of energy that enters the earth's atmosphere that

## II. Studies of Solar Energy Transmission

### A. Relatively Clear Atmosphere

arrives finally at the ground at each of the stations); the visibility for the previous hour (in miles); about six or eight columns of data describing the weather such as fog, dust, haze, smoke, etc.; the dry bulb and the dew point temperatures from which can be computed the relative humidity; the amount of total clouds in fractions of the total sky covered; and separate information on each of up to as many as four successive layers of clouds, the height of each cloud layer plus the fractional part of the sky covered by that layer, and the type of cloud constituting that layer. (It is to be noted, however, that very seldom is there data in existence for as many as four cloud layers.)

In using this data, it should be kept in mind that most calculations of transmissivity are for a surface optimally oriented to receive the greatest amount of radiation. Thus in determining, for example, the attenuation due to cloud cover from this data, one must correct the fractional transmission factor since all the data is for a horizontal surface. With a cloud cover the radiation is very nearly isotropic and would therefore irradiate almost equally a surface oriented in any direction except, of course, downward. However, the direct radiation would be enhanced on optimally oriented surface, especially for low sun angles by just the cosecant of the solar elevation angle. Hence, the column giving percentage of possible radiation is very definitely an upper limit to the transmissivity of the cloud layer to an optimally oriented surface.

- b. Moore, A. F. and L. H. Abbot, The Brightness of the Sky, Smithsonian Miscellaneous Collections, 71 (4), February 4, 1920

This paper describes sky brightness measurements performed in North Carolina from June 1917 to April 1918 at an altitude of 4800 feet (at 36°N latitude). Total radiation to a horizontal surface and direct radiation to a surface perpendicular to the solar rays were measured for a wide variety of haze and other weather conditions. This paper contains a wide variety of observations that in some instances are unique in the published literature. Of particular interest are the direct radiation totals and the diffuse and the total radiation for particular instances in time at which the sun is low in the sky (pp.8-12). The degree of haziness or cloudiness is verbally described but it gives some indication of what one might expect in transmission for low elevation angles.

- c. Kimball, H. H., Solar Radiation Intensities within the Arctic Circle, Monthly Weather Review 59, 154 (April 1931)

This paper describes measurements of solar energy at very low angles in the sky from the Arctic. It is apparent that many of the sky conditions encountered there were exceptionally clear compared with those around industrial cities of the United States. However, these measurements serve as useful corroborations of theoretical calculations for the for the exceptionally clear condition.

## II. Studies of Solar Energy Transmission

### A. Relatively Clear Atmosphere

- d. Kimball, H. H., Measurements of Solar Radiation Intensity and Determinations of its Depletion by the Atmosphere with Bibliography of Pyrhelometric Measurements, Monthly Weather Review 55, 155 (April 1927)

A rather complete bibliography and summary of measurements of total solar energy incident upon a horizontal surface. Most of the measurements that are described or summarized in this paper are oriented toward determination of the solar constant, although they have a great deal of significance to determination of the atmospheric transmissivity on the average cloudless day at a given station. Monthly means of the solar radiation and atmospheric transmission for locations all over the earth are given in an extensive set of tables.

- e. McCormick, R. A., Atmospheric Turbidity Reports, Weather Bureau of Research Station, Laboratory of Engineering and Physical Sciences, R. A. Taft Sanitary Engineering Center, Cincinnati, Ohio

These reports can be obtained from the author in their original form. Only long-time averages of them usually get published in the open literature. They contain, for some 30 stations in the United States, measurements at several instants during the day of the transmission of solar energy at 0.5-micron wavelength.

A Volz sun photometer is used in the measurement. This is a collimated detector which receives radiation only within a cone of one degree of arc centered on the sun. An interference filter excludes all radiation except that near 0.5 micron. Since the diameter of many of the haze particles in atmospheres about cities, is, or may be, in the range 0.1 to 0.5 micron, these results on the transmission of 0.5-micron radiation are asserted to give a measure of the atmospheric content of the haze particles.

Although only the direct component of solar radiation is measured, these measurements may be more realistic in determining the transmission of radiation from high altitude nuclear bursts than are the more common measurements of the total solar spectrum. These 0.5-micron measurements are made only for cloudless conditions, or for conditions where the cloud-free zone about the sun is some  $30^{\circ}$  of arc on partly cloudy days. Hence, potentially, it gives a source of data which will be useful primarily in determining atmospheric transmission for hazy or smoggy days.

- f. Kauper, E. K., Air Pollution Control District, County of Los Angeles, 434 S. San Pedro St., Los Angeles 13, California, private communication (1962)

Mr. Kauper possesses some unpublished data of particular interest in the determination of the effect of haze on atmospheric transmission. One three days, July 6, July 27, and August 1, 1962,

## II. Studies of Solar Energy Transmission

### A. Relatively Clear Atmosphere

a helicopter was employed with a Volz sun photometer (see II-A-2e) receiving in the wavelength region near 0.5 micron only, readings being taken at intervals of 200-foot altitude from 600 feet to the top of the local haze layer. The flights were repeated each hour, giving a total of 7 or 8 separate flights each day. These data may prove to be of particular value in evaluating the transmission of smoggy atmospheres of types common to the Los Angeles basin.

- g. Levine, M. and E. Simon, Atmospheric Transmission of Solar Radiation, Internal Report No. LTM-50244, Lockheed California Co., Burbank, California, October 12, 1962

This report (unpublished) describes measurements of the solar radiation at 20A intervals between 3000A and 3500A on some 9 or 10 smoggy days in late 1961. The radiation detector was collimated to receive only the direct component from the sun. These investigators observed a general depression in the amount of ultraviolet energy arriving from the sun on the smoggy hours, the transmission at 3500A being a factor of 2 to 6 below that of a clear day. These data may be a valuable source of information for this particular wavelength region for the scattering coefficients of atmospheres and smog common to the Los Angeles basin.

- h. Steinhauser, F., Die Zunahme der Intensitat der direkten Sonnenstrahlung mit der Hohe im Alpengebiet und die Verteilung der "Trubung" in den unteren Luftschichten, Meteorologische zeit. 56, 172-181 (1939)

The paper (in German) describes an experimental study of the intensity of the direct sun's rays at different heights in the Alps. A table is given of the solar energy arriving at a surface perpendicular to the sun's rays for solar elevations of 5° up to 65° in 5° steps for every month of the year at altitudes of 200, 500, 1000, 1500, 2000, and 3000 meters. A detailed analysis of this paper should give some useful information on the attenuation of the direct component of solar energy by haze particles.

- i. Pazsynski, J., Actinometry in the Research Work of the Polish Expedition to Vietnam, IGY 1957/58, Acta Geophysica Polonica (Warsaw) 7, 230 (1959)

Although the actual reference (in Polish) does not contain any data, microcards of the data described in the reference can be obtained from the International Geophysical Year World Data Center A, National Academy of Sciences, National Research Council of the United States of America, 2101 Constitution Avenue, Washington 25, D.C. These data are of several kinds: first, the daily sums of radiation both direct and total, for Chapa, Vietnam, at 22°, 21'N latitude, and 103°, 49'E longitude, for the years 1958 and 1959. In addition, instantaneous intensities of direct solar radiation at three separate wavelengths, namely, 0.53, 0.63, and 0.70 micron were obtained for numerous times on cloudless days for the same location.

## II. Studies of Solar Energy Transmission

### B. Cloudy Atmospheres

#### 1. Theoretical

- a. Schuster, A., Radiation through a Foggy Atmosphere, *Astrophysical Journal* 21, 1 (1955)

In this paper equations are derived to calculate the amount of energy transmitted through a layer of fog or cloud. The paper is directed toward predicting the emissions of the atmospheres of stars and hence it deals with problems in addition to those of importance to solar energy transmission through a cloud layer. Many of the later papers on the theory of transmission through a cloud refer to this paper in which the basic differential equations are derived and solved under simplified assumptions.

- b. Hewson, E. W., The Reflection, Absorption and Transmission of Solar Radiation by Fog and Cloud, *Quart. J. Royal Meteor. Soc.* 69, 47-62 (1943)

This paper shows the development of a system of equations from which may be computed the fractions of the sun and sky radiation, incident on a fog or cloud which will be reflected, absorbed and transmitted. These fractions are found to vary with the size of the droplets, the thickness of the fog or cloud, and the density or amount of liquid water/meter<sup>3</sup>.

A very small variation is observed in these parameters with changing elevation of the sun above the horizon, probably because the author considers only horizontal receivers. The writer assumes fog to have particles typically 20 microns in diameter, and that clouds have particles typically 5 microns in diameter. For three values of the water density (0.1, 1.0, and 5.0 grams/meter<sup>3</sup>) and for cloud thicknesses of 20, 80, 200, 1000, and 4000 meters, Table I gives the theoretically computed values of the fractions of incident radiation which are scattered, absorbed, and transmitted. One of the results of interest to this study is that a cloud must have a thickness about 150 meters at a density of 1 gram/meter<sup>3</sup> of liquid water before it can reflect 80% of the incident radiation. However, a more dense cloud of 5 grams/meter<sup>3</sup> of water vapor need be only 50-meters thick to reflect 80% of the incident radiation. It is significant that the highest values of the absorbed fraction in the most dense cloud considered reached no higher than 0.10.

- c. Korb, G., J. Michalowsky, and F. Moller, Absorption of Solar Radiation in Cloudless and Cloudy Atmospheres, *Beit. Phys. Atmosphere*, 30, 63 (1957)

This paper provides a calculation of the transmission, reflectance, and absorption of several particular cloud types and thicknesses. Contrary to the results of Hewson (II-B-1b) above, substantial effects

## II. Studies of Solar Energy Transmission

### B. Cloudy Atmospheres

due to the sun's elevation angle above the horizon are noted. Figure 4 of the paper summarizes the results of interest to the present problem; for example, a cumulus cloud of 100-meter thickness is shown to reflect some 94% of the solar energy when the sun is  $10^\circ$  above the horizon and some 78% when the sun is at the zenith. By comparison a 300-meter thick cumulus cloud reflects 80% of the energy when the sun is  $10^\circ$  above the horizon, but only about 50% when the sun is at the zenith. Since absorption is never more than a few percent, the reflectivity of a cloud when subtracted from 100% gives the transmission. A stratus cloud of 200-meters thickness is calculated to have a reflectivity of about 70% with the sun at  $10^\circ$  elevation, and about 38% with the sun at the zenith.

- d. Fritz, S., Solar Energy on Clear and Cloudy Days, Scientific Monthly 84, 55-65 (1957)

This paper is one given before the conference on "Solar Energy, the Scientific Basis" that was held October 31 to November 1, 1955, jointly sponsored by the University of Arizona and Stanford Research Institute. The theoretical calculation of transmittance of clouds is treated in this paper in terms of the sun's zenith distance and the thickness of the cloud. The thickness of the cloud is in terms of the number of mean free paths of the radiation in its passage through the cloud. The mean free path referred to is given by the equation  $L = (\Sigma N \pi r^2)^{-1}$ , where  $r$  is the radius of the droplets in the cloud, and  $N$  is the number of droplets per cubic centimeter.

The albedo of the earth's surface is also included in this treatment of the transmittance of clouds. The curves for the surface albedo of zero are of prime interest to the problem at hand. To determine the mean free path  $L$ , one must know the size of the water droplets and the total liquid water present per cubic meter in the cloud.

The author concludes that since one seldom is able to obtain information on liquid content and drop size of a given set of clouds, one must depend entirely on correlations with more subjectively measured parameters such as the opacity of the sky and fractional coverage by cloud, and/or the fraction of sunshine hours in a given location. The nonhomogeneous nature of many common clouds is stated to be another source of uncertainty in predicting the transmission of solar energy through clouds.

## 2. Experimental

- a. Aldrich, L. B., The Reflecting Power of Clouds, Appendix III, Annals of Astrophysical Observatory of the Smithsonian Institution 4, 375 (1922)

This paper reports measurements of the albedo of a thick fog blanket from 180-meters thick to 500-meters thick over the Los Angeles basin. The measurement was made on September 17, 1918, using a manned, captive balloon. Radiation from the entire hemisphere looking down from

## II. Studies of Solar Energy Transmission

### B. Cloudy Atmospheres

the balloon above the fog blanket was compared with that observed in the entire hemisphere looking up from the balloon. The average of all the measurements showed the reflectivity of the fog blanket to be 78%. Individual measurements ranged from 70% reflectivity to 90% reflectivity. The lowest reflectivity was observed for the sun closest to the zenith, but in general no evidence of a change of reflecting power with a change in solar elevation was observed. This particular fog blanket was particularly homogeneous and dense with a very level top and hence might not be representative of all cloud cover.

- b. Neiburger, M., Reflection, Absorption and Transmission of Insolation by Stratus Cloud, J. Meteor. 6, 98 (1949)

Using Eppley pyrheliometers mounted on a blimp, observations were made of the upward and downward flux of short-wave radiation, above, in, and below California coastal stratus throughout the summer of 1945. The observations are summarized and evaluated in terms of the percentage of the incident radiation reflected, absorbed, and transmitted as a function of the thickness of the cloud. The primary conclusions from this paper are that simple theories when compared with the experiment show differences which can be attributed to the various simplifying assumptions in the theoretical treatments.

For example a theory usually assumes a constant liquid content as a function of position in the cloud whereas the measured liquid content in California stratus studied here increased linearly from the bottom of the cloud to the top of the cloud. At the bottom of many clouds, the liquid water content in grams per cubic meter would be of the order of 0.1 and would increase to 0.5 at the top of the cloud; the cloud thickness being approximately 500 meters. The drop size measured in these clouds studied usually had a well-pronounced peak around 13-15 microns diameter. This paper appears to be one of the best experimental studies of the reflectivity from clouds and the absorption in clouds of any that have to this author's attention.

- c. Kikuti, Y., M. Yamazaki, T. Okawa, and Y. Morita.  
Transmission of Solar Radiation through Fog, Geophysical Magazine (Tokyo) 26(1), 83-92 (1954)

These measurements were performed using a captive, unmanned balloon on the southeastern coast of the island of Hokkaido during the summer of 1953. The observations were made during the period from the 12th to the 23rd of July and mostly early in the morning. Figure 6 of the paper gives results of the measurements of the transmission of solar energy down through the fog as a function of the thickness of fog above the balloon.

The measurements show approximately 20% transmission for fog blankets between 230- and 280-meters thickness, 40% transmission for fog blankets around 140 meters, 60% transmission at 80-meters thickness, and 80% transmission at 20-meters thickness. The liquid water content



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### B. Cloudy Atmospheres

in the fogs measured in this paper range near  $0.25 \text{ g/cm}^3$ . Since these measurements represent only about 18 separate determinations, they have somewhat limited value.

- d. Haurwitz, B., Insolation in Relation to Cloud Type, J. Meteor. 5, 110-113 (1948)

Using insolation data during the eight years from 1938 to 1945 that were collected at the Blue Hill Observatory in Milton, Mass., hours with complete overcast were correlated with the amount of simultaneous insolation and sorted according to cloud type.

The results can be summarized as follows: for cirrus clouds transmission of solar energy was about 85% relative to the cloudless sky; alto-cumulus and alto-stratus transmit 52 and 41% respectively; strato-cumulus, 35%; stratus, 25%; nimbo-stratus, 15%; and fog, 17%. These percentages were roughly independent of the elevation of the sun, but it must be kept in mind that the percentages represent the relative amounts of energy arriving on a horizontal surface. For an optimally oriented surface (normal to sun's rays) the radiation incident from a cloudless sky would be greater than the radiation on a horizontal surface by a ratio equal to the cosecant of the elevation angle, whereas the measurement on the horizontal surface made with cloudy skies would be very similar to those measured on any other surface orientation. Hence, in comparing this insolation data with the kind of transmission data required for calculation of transmission to an optimally oriented surface, one must divide each transmission by the cosecant of the angle of elevation of the sun.

- e. Arnulf, A., J. Bricard, E. Cure, and C. Veret. Transmission by Haze and Fog in the Spectral Region 0.35 to 10 Microns, J. Opt. Soc. Amer. 47, 491-498 (1957)

A large number of hazes and fogs were studied with regard to their spectral transmission from a carbon arc source to a collimated receiver. A total of 600 spectrophotometric curves were obtained, of which 250 were for hazes, 15 for selective types of fogs, 167 for evolving fogs, and 168 for non-evolving large drop fogs. It was found that the transmission of haze increased markedly with the increasing wavelength from the visible to 10 microns, but this marked increase was not found for fogs. Drop size measurements were made in connection with all these experiments for the fogs, but the particle diameter of the haze particles was not measured. The average or most common particle size observed in the fog studied was of the order of 3 microns, although the population was still significant up to about 15 microns. This paper is a good source of fundamental data.

## II. Studies of Solar Energy Transmission

### B. Cloudy Atmospheres

- f. Fritz, S., Solar Radiant Energy and Its Modification by the Earth and its Atmosphere, Compendium of Meteorology, H. R. Byers, et al., ed. by T. F. Malone, Boston Meteorological Society (1951)

This paper is a section of a large reference volume on meteorology. It deals particularly with the absorption of solar energy on the earth's atmosphere. It is a compilation of a large amount of experimental data and serves as a useful summary of the problem.

- g. Thomson, A., Solar Radiation Observations at Apia, Samoa, Monthly Weather 55, 266 (1927)

This paper reports some very useful information on the transmission of the atmosphere at a very humid sea level site. However, the data were taken only on clear days, so that its chief value is in the assessment of the effect of atmospheres associated with high humidity on the transmission of solar energy. Average measurements down to optical air masses of 5 are given for the dry season, the wet season and the equinoctial season.

- h. Stair, R., The Spectral Radiant Energy from the Sun through Varying Degrees of Smog at Los Angeles, Proc. Third Natl. Air Pollution Symposium, pp.48-55 (April 1955)

This paper gives some experimental transmission data as a function of wavelength of the light for several days in 1954 in Pasadena, California, on which smog was particularly evident. Its main objective was to determine some of the characteristics of smog, but the data in some cases may be directly applicable to the present problem.

- i. Mahoney, J. J., D. D. Keogh, and D. T. Kilminster, Thermal Attenuation by Chemical Smokes, U.S. Army Chemical Warfare Laboratory Technical Report AD-233586, CWLR 2353 (January 1960)

Using a carbon arc source, a number of different smokes were investigated as to their ability to reflect or absorb thermal radiation. The six smokes used were fog oil; naphthalene (carbon), titanium tetrachloride; chloro-sulfonic acid-sulfur trioxide; hexa-chloroethane; and silicon tetrachloride-ammonia. The chief result of interest is their conclusion that an absorbing smoke such as finely divided carbon is more effective by a factor of about 4 than a scattering smoke in reducing thermal radiation from a 6000°K source for smoke concentrations of 0.5 g/m<sup>2</sup>. The transmissivity, for example, for a 1 g/m<sup>2</sup> (along the path of the radiation) carbon smoke is 4%, whereas for a white titanium tetrachloride smoke, the transmissivity is approximately 50% for the same concentration by weight.

## II. Studies of Solar Energy Transmission

### B. Cloudy Atmospheres

- j. Essenwanger, O. and G. Haggard, The Relation between Cloud Cover and Relative Humidity, Report No. USAOMC RR-TR-61-33, U.S. Army Ordnance Missile Command, Redstone Arsenal, Alabama, December 15, 1961

This paper gives the correlation between the degree of cloud cover for Berlin and Omaha, Nebraska, with the relative humidity measured at several different altitudes above the ground. With similar correlations of a more detailed nature, it may be possible with a simple measurement of relative humidity versus altitude to determine more detail about the thickness and extent of clouds than is now possible from visible observations. While this paper does not explore this possibility completely, it is a good starting point.

- k. Summary of Constant Pressure Data, WBAN-33, National Weather Records Center, Asheville, North Carolina

This reference is included to describe the nature of a large volume of data that is continually collected and disseminated from the National Weather Records Center. The data consist of relative humidity, wind speed, and temperature as a function of height above each of these stations for 0 and 1200 Greenwich mean time. The altitude interval is about 50-mb pressure or approximately every 500 meters for the first 10 km or so. This interval is inconveniently large to determine the exact extent of cloud cover; however, it is possible to obtain more frequent soundings from the original source from which these records were punched onto cards. The usefulness of these records in determining the extent of cloud cover depends on the assumption that relative humidity near 100% is indicative of the presence of cloud. There is a definite possibility that for every station which sends up radiosondes born by balloons, and which also simultaneously measures the energy from the sun, one can obtain a statistically significant amount of data on the relation between cloud thickness and transmission of solar energy.

- l. Jones, L. A. and H. R. Condit, Sunlight and Skylight as Determinants of Photographic Exposure. I. Luminous Density as Determined by Solar Altitude and Atmospheric Conditions, J. Opt. Soc. Amer. 38, 123 (1948)

This paper describes an extensive series of calculations and measurements designed to allow predictions of required photographic exposures for a wide range of atmospheric conditions. The various atmospheric conditions are described in detailed verbal terms. The authors conclude that the main variable determining photographic exposure is the luminous density, defined as the luminous energy per unit volume regardless of the direction of the rays. The increased exposure required under given atmospheric conditions can be taken directly as the relative attenuation of a given atmospheric condition. This assumes that the radiation spectrum from nuclear bursts is not far different from the standard visibility curve. Transmission on the

## II. Studies of Solar Energy Transmission

### B. Cloudy Atmospheres

average clear day was computed by these authors basically from the data of Moon (see II-A-1f). The authors present experimental data on varying degrees of haze and cloud relative to 1.0 for the average clear day at sea level. Representative transmissions (for an optimally oriented surface) are 0.70 for light haze, 0.5 for medium haze, 0.32 for heavy haze or light cloud, 0.2 for medium cloud, 0.1 for heavy cloud, and 0.03 for dense cloud.

<p>ASTIA NO.</p> <p>STANFORD RESEARCH INSTITUTE, Menlo Park, California</p> <p>TRANSMISSION BY THE EARTH'S ATMOSPHERE OF THERMAL ENERGY FROM NUCLEAR DETONATIONS ABOVE 50 km ALTITUDE, by T. Passell Technical Report, May 1962 to May 1963, 64 pp. 11 Figs. UNCLASSIFIED</p> <p>SRI Project 4021-302, Contract OCD-OS-62-135 (III)</p> <p>The extensive literature on transmission of radiation from the sun by the earth's atmosphere supports transmission estimates varying from 80% for vertical rays to 15% for rays 5° above horizontal for the average clear day at sea level. Cloud transmission (on the basis of 100% for a clear day) varies from around 30% for light cloud to 3% for a dense cloud. Theoretically estimated upper limits to the unattenuated energy</p>	<p>UNCLASSIFIED</p> <ol style="list-style-type: none"> <li>1. Nuclear Weapons</li> <li>2. High Altitude</li> <li>3. Thermal Radiation</li> <li>4. Atmospheric Transmission</li> </ol>
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<p>flux from a 1000 mt detonation (taken from a companion study) combined with the above estimates of atmospheric transmission gives ignition radii ranging from 250 km at 50 km burst height to zero km at 240 km burst height (on an average clear day). Ignition is assumed to require 10 calories/cm<sup>2</sup> delivered in 1 second.</p>	<p>UNCLASSIFIED</p>	<p>flux from a 1000 mt detonation (taken from a companion study) combined with the above estimates of atmospheric transmission gives ignition radii ranging from 250 km at 50 km burst height to zero km at 240 km burst height (on an average clear day). Ignition is assumed to require 10 calories/cm<sup>2</sup> delivered in 1 second.</p>	<p>UNCLASSIFIED</p>
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